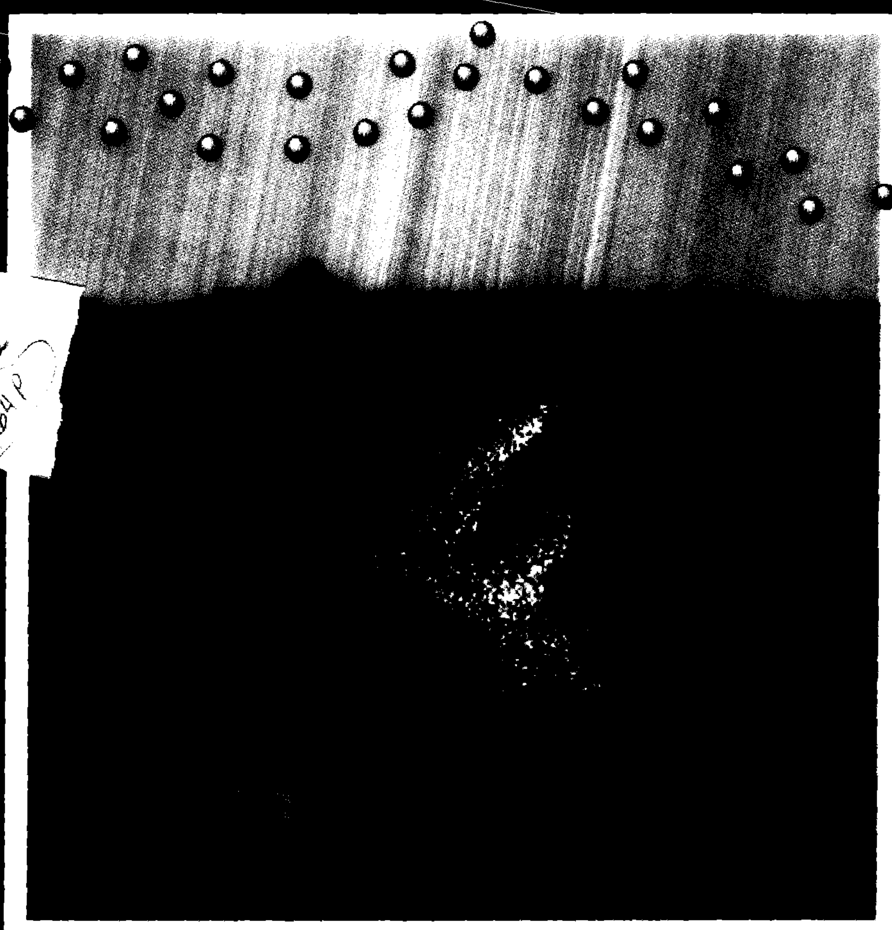
Lawrence Livermore National Laboratory

UCRL-51444-90/91

Atmospheric and Geophysical Sciences Program Report 1990–1991



(Front Cover)

Simulation of Toxic-Vapor Dispersion

On July 14, 1991, a railroad tank car derailed and spilled about 19,000 gallons of metam sodium herbicide into California's Upper Sacramento River approximately 3 miles north of Dunsmuir, California. The river flows directly into the northernmost finger of California's largest reservoir and popular recreation area, Lake Shasta. The question of whether or not to evacuate residents and vacationers along the Sacramento River arm of Lake Shasta led California's Office of Emergency Services (OES) to ask the Atmospheric Release Advisory Capability (ARAC) center to use its dispersion modeling capabilities to determine the maximum credible air concentrations that could be expected from the evaporation of the herbicide. The visualization shown on the front cover is the model-generated estimate of the herbicide plume (shown here by a set of marker particles) from an evaporating surface layer on Lake Shasta's North Fork. The plume is being carried toward the north-northeast and is channeled by the complex terrain. Mount Shasta is on the horizon and the Sacramento River gorge is to the left of the plume.

(Back Cover)

Smoke Plume from the Kuwaiti Oil Fires: Observed and Simulated

When Operation Desert Storm ended on February 28, 1991, scientific attention began to focus on the possible consequences of the spreading smoke plume from the oil fires in Kuwait. The Atmospheric Release Advisory Capability (ARAC) center was asked to perform calculations in support of plume sampling flights flown by U.S. research groups to improve understanding of the character of the smoke particles and of the potential environmental impacts of the plume. The back cover (lower panel) shows a simulated forecast of the plume's structure and location prepared by ARAC for the May 8, 1991, U.S. research flights. The upper panel is a photograph of the plume taken by a weather satellite at the approximate time of the forecast, showing considerable agreement with the model calculations.

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Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Atmospheric and Geophysical Sciences Program Report 1990–1991

Physics Department
Lawrence Livermore National Laboratory

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Art and Design: Kenneth M. Ball
Manuscript Date: June 1992

UCRL-51444-90/91
Distribution Category UC-403

Acknowledgments

This report documents the scientific and technical activities of the Atmospheric and Geophysical Sciences (AGS) Program for the calendar years 1990 and 1991, with some carryover into 1992. The articles are based on input from the Program's scientists and group leaders. As co-Scientific Editor, James Albritton helped greatly in bringing consistency to the approach and content of the research articles. Dianna Leap collected and prepared the draft input and coordinated the reviews. Information in the appendices was assembled by Camille Vandermeer, Floy Worden, Pamela Drumtra, and Raylene Cooper. In addition, Raylene Cooper provided technical publication assistance, Pamela Drumtra provided administrative support, and the administrative support staff provided clerical assistance. The editing of the report was led very ably by Pamela MacGregor of the Technical Information Department with assistance from Elaine Price and Jay Cherniak. Kenneth Ball of the Technical Information Department designed the report, coordinated the layout, and transformed the draft input for the graphics into final form; Pamela Allen and Irene Chan prepared the layout. The dedication and commitment of all of these people in preparing this report is greatly appreciated.

For further information, individuals mentioned in this report may be reached through the Atmospheric and Geophysical Sciences (G) Division Office at (510) 422-1800. For copies of publications, please contact the G-Division Librarian, Lawrence Livermore National Laboratory, P.O. Box 808, L-262, Livermore, CA 94551.

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Preface

Section 1 presents an overview of the Atmospheric and Geophysical Sciences (AGS) Program at Lawrence Livermore National Laboratory (LLNL). In recognition of the Laboratory's fortieth anniversary, this section also includes a historical overview of the AGS Program. We look back to the origins of AGS research in the 1950s and 1960s, recognizing the contributions of those who led the two "taproots" of our current activities. We then describe some of the highlights of our projects during the 1970s and 1980s—projects that brought many of the current staff to the Laboratory. We emphasize that this is only an overview, and extend our apologies and gratitude to those whom we may have unintentionally omitted.

Section 2 of this biennial report is a series of eight articles contributed by our two major programs and six topical groups. Each article provides background material for context and highlights of our progress in research activities during 1990 and 1991, although some spillover into 1992 is included.

Section 3 consists of seven appendices that provide more detailed information about the AGS Program. Appendix A describes our staff, and Appendix B describes our interactions with outside collaborators. Appendix C lists our funding in detail, Appendix D summarizes our current modeling capabilities, and Appendix E lists our publications and reports. Finally, Appendix F lists the visitors who have presented AGS seminars at LLNL, and Appendix G defines the many acronyms and abbreviations used in this report.

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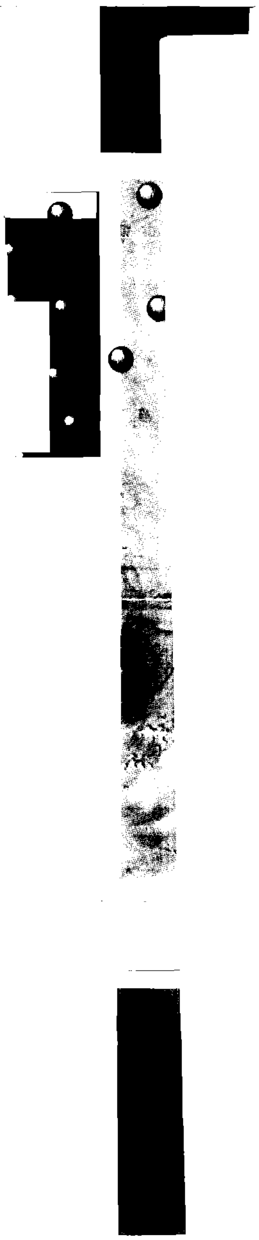

Atmospheric Release Advisory Capability (ARAC) Center
At the onset of the 1991 Operation Desert Storm crisis, the ARAC center was asked by the U.S. Department of Ene Emergency Operations Center (EOC) to provide immediate assistance in assessing the possible consequences of ev triggered by Desert Storm. This photograph shows the ARAC operations staff working with some of the products pr by ARAC during and after Desert Storm. Proceeding clockwise from the foreground: weather-forecast charts, 36-hr of soot dispersion from the oil-field fires, and 36-hr forecast of particle flow over the terrain. The screen in the bac! displays an image of a burning oil well. Staff: foreground, Ron Baskett, assessment meteorologist; background, Ton computer technician.

Program Overview

The goal of the Atmospheric and Geophysical Sciences (AGS) Program at the Lawrence Livermore National Laboratory (LLNL) is to contribute to advancing and improving the understanding and resolution of atmospheric and geophysical science issues of broad national and international significance. Our research emphasizes the development and application of carefully formulated and verified numerical models of the atmosphere-geosphere system. We focus on the study of the effects of energy- and defense-related emissions on the environment, and we apply advanced emergency response models to consequence assessment and mitigation of high-impact, technological accidents involving atmospheric releases of radioactive or other hazardous materials.

Stimulated by environmental issues of wide public interest, the scope of the applied and operational research activities included in the AGS Program intensified significantly during 1990–91. The potential consequences of an increased greenhouse effect and of stratospheric ozone depletion led to expanded efforts to simulate the global climate and atmospheric chemistry system and to better understand the confidence that can be placed in calculations made by these models. The threat and consequent development of environmental impacts associated with the Persian Gulf War led to an unprecedented demand for the services of our Atmospheric Release Advisory Capability (ARAC). During Operation Desert Storm, ARAC was asked to model the dispersal of smoke emissions and the hypothetical dispersal of chemical warfare agents. After the war, ARAC provided researchers and environmental agencies in the Gulf region with continuing forecasts of the changing positions of the spreading smoke plumes from the oil fires in Kuwait. Numerous other challenges and opportunities also led to interesting applications and to the expansion of our capabilities.

Research Themes

Our research falls under two principal thematic areas: (1) accident preparedness and emergency response, which includes exploring the role of the atmosphere in the dispersal, transformation, and deposition of radionuclides, particles, trace gases, and toxic and heavier-than-air gases; and (2) global change, which includes studying the perturbing effects of emissions such as carbon dioxide, aerosols, chlorofluorocarbons, and other trace gases on the climate and on the composition and chemistry of the atmosphere. Within these areas, our specific activities range across a wide spectrum from applied to operational.

The accident preparedness and emergency response area is concerned with both the hypothesized and realized consequences of natural and human-induced hazardous phenomena that affect the environment and human exposure. ARAC is the designated national response center in the event of potential and actual releases of radionuclides to the environment, and our emergency-response personnel are responsible for providing projections of radionuclide transport and dispersion in real-time. We are working with scientists from the former Soviet Union to improve radionuclide dispersion models by using data from the Chernobyl nuclear reactor accident. We are also continuing to develop techniques to evaluate the risks associated with accidents involving nuclear weapons. We have tested a new implementation of our model that describes the spread of heavier-than-air gases; we will be using it to augment and improve our capabilities for assessing hazardous toxic material accidents.

Our research in the global change area includes studies of climate change and biogeochemical cycles, focusing especially on model development and on comparisons of model results with observations. In support of these efforts, our Program for Climate Model Diagnosis and Intercomparison (PCMDI) is leading the Atmospheric Model Intercomparison Project (AMIP), which involves working with nearly 30 atmospheric modeling groups from around the world to evaluate how well models can simulate the observed climatic conditions over the period 1979 to 1988. We are also developing three-dimensional global chemistry models to study the processes that control the concentrations of ozone and other species from the boundary layer up through the stratosphere. As the lead theoretical modeling team for the Upper Atmosphere Research Satellite, we are comparing model calculations of stratospheric constituents with satellite observations. For the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program, we are developing and implementing the experimental protocols that will link the research scientists with the observations being taken at ARM field sites. To provide the models needed to study critical questions relating to the natural variability of the climate system, regional climate change, and chemistry-climate coupling, we are implementing and optimizing global climate and chemistry models on the latest massively parallel computers for the DOE's Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) program. To simulate the response of the integrated Earth system, we are developing and coupling models of the atmosphere, ocean, and biosphere. Finally, we are working with a special group of school teachers to develop, test, and disseminate multidisciplinary curriculum materials that focus on the scientific, social, historical, and mathematical aspects of the greenhouse effect.

Research Staff

In pursuit of these activities, our research program has grown to include more than 150 scientific, technical, and administrative staff. This number reflects about a 40% growth in our program over the past two years, principally because we have more graduate students, postdoctoral fellows, and term appointees, in addition to more scientific, computational, and other technical staff assigned to support our programs from other Laboratory departments. Because the scope of our research has expanded, an increasing number of scientists from around the Laboratory has also become involved in our projects.

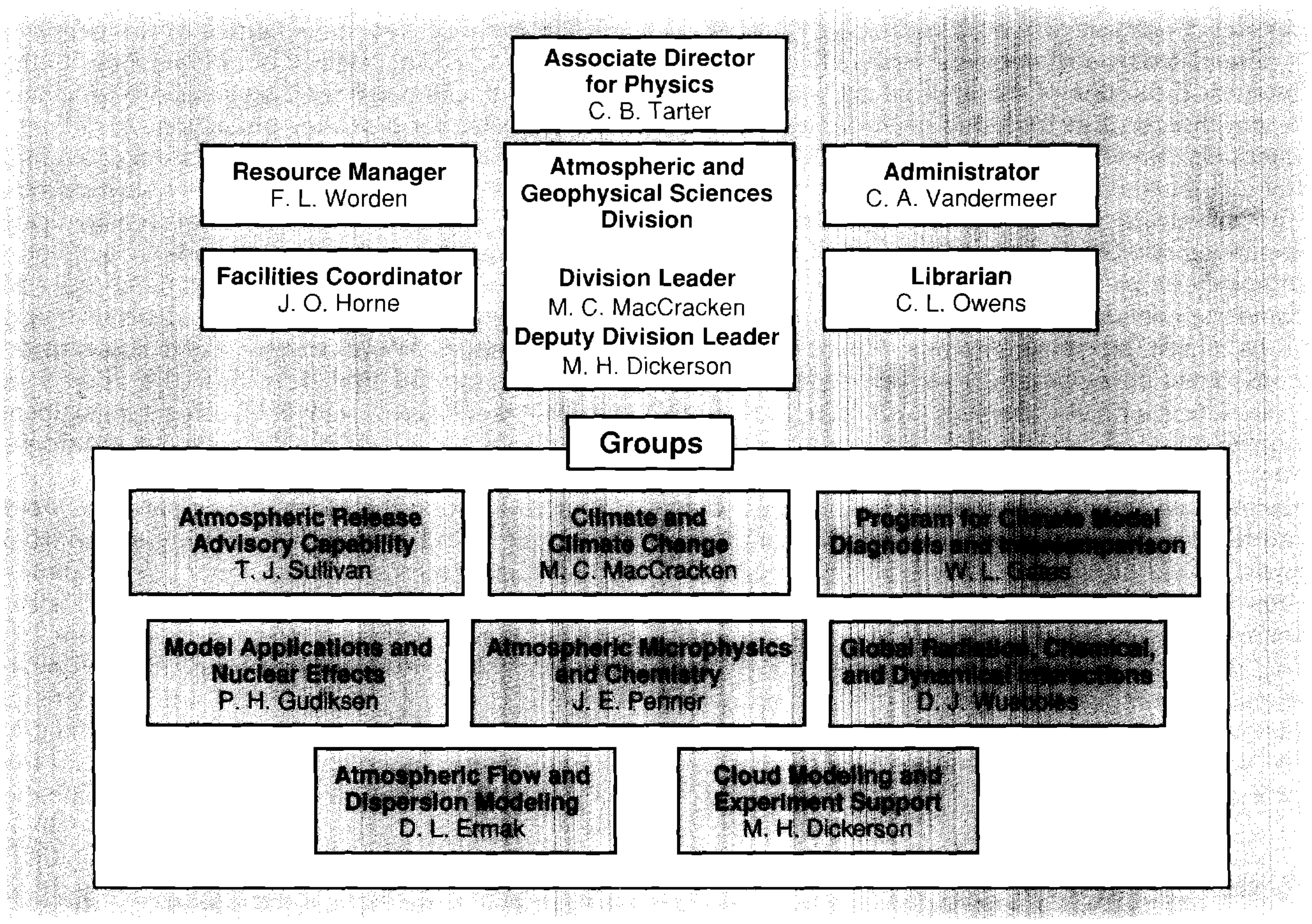

Figure 1. Organizational structure of G-Division.

Research Collaborations

The extent and depth of our interactions with scientists outside the Laboratory have also expanded significantly. These activities range from development of new scientists to collaborations with national and international research groups. For example, within the University of California, the impetus of the Institutional Collaborative Research program (which now includes the Davis, Irvine, and Los Angeles campuses, Scripps Institution of Oceanography, Los Alamos National Laboratory, and LLNL) has intensified efforts to model the atmosphere, oceans, and sea ice. The PCMDI's comparison studies are another example of how our interactions with others have expanded. Many of the modeling organizations who are participating in the AMIP use the computers at LLNL's National Energy Research Supercomputer Center to conduct and analyze simulations and to gain access to new graphics analysis tools developed by PCMDI. This synergy of laboratory-university and of laboratory-laboratory interactions greatly enriches our research program and, we believe, those of others.

Organization

The AGS Program at LLNL is led by the Atmospheric and Geophysical Sciences (G) Division, which is part of the Physics Department; additional scientific, technical, and support staff are matrixed to or collaborate with the Division to help carry out the applied and operational research activities. The Division is organized into eight groups, two of which are major programmatic efforts (ARAC and PCMDI) and six of which focus on particular topical areas (Figure 1). These groups are led by researchers active in their field and include scientists from within and outside G-Division. Each group's projects encompass a set of topically related projects. Considerable interaction takes place among the groups, and a number of staff members participate in the projects of more than one group. Our emphasis on research themes and topical areas provides the opportunity for collaborative and team-oriented projects, which we believe is a distinction of the Laboratory's research programs.

The Division's organizational structure also allows for considerable interaction between those groups focusing on global change and those emphasizing accident preparedness, emergency response, and assessment. Two examples are illustrative: (1) ARAC and the Atmospheric Microphysics and Chemistry Groups were both involved in our studies of the smoke plumes from the Kuwaiti oil fires; and (2) the Atmospheric Flow and Dispersion Modeling Group is developing capabilities that can be used for both the mesoscale prediction for ARAC and for the study of mesoscale climate change in the context of global climate modeling.

Funding

Our funding sources reflect the variety of our research activities. As indicated in Figure 2, almost 70% of our funding is from the DOE. Most of this funding comes directly from the Environmental Sciences Division, the Office of Defense Programs, and other DOE offices; in addition, some DOE funds are passed to us through other laboratories and organizations. Almost 20% of our funding is from other federal agencies such as the National Aeronautics and Space Administration, the Environmental Protection Agency, and the U.S. Department of Defense (DOD). About 10% of our

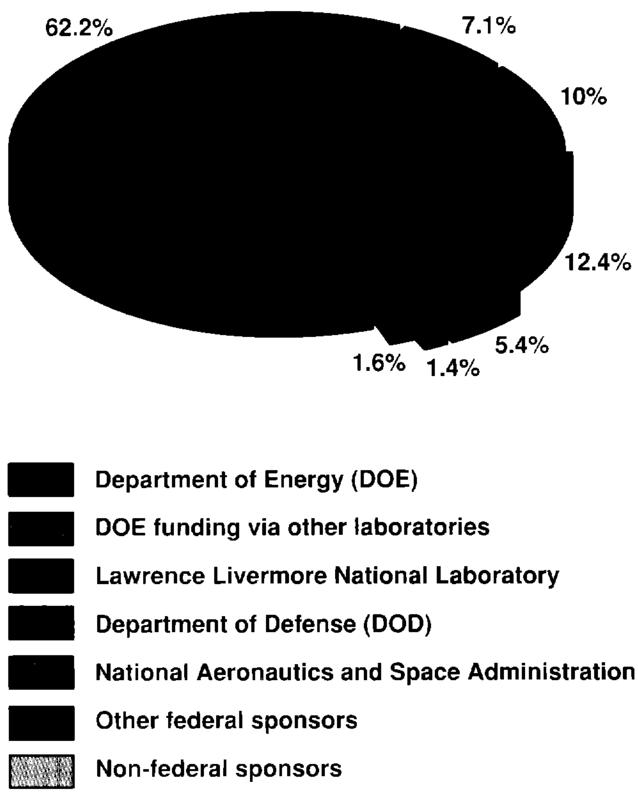

Figure 2. FY92 budget by funding agency for the G-Division-led Atmospheric and Geophysical Sciences Program.

funding is from internal Laboratory funds for research and environmental studies. The remaining 1.6% of our funding is from industry and other non-federal sources.

Figure 3 indicates the distribution of our funding across the Division's groups. ARAC and PCMDI each receive substantial support from their sponsors for their special activities. The other six groups are generally supported by a large number of more modest projects. In overall funding, the thematic area of global change accounts for about 60% of the funding, and the thematic area of accident preparedness, emergency response, and assessment accounts for about 40%.

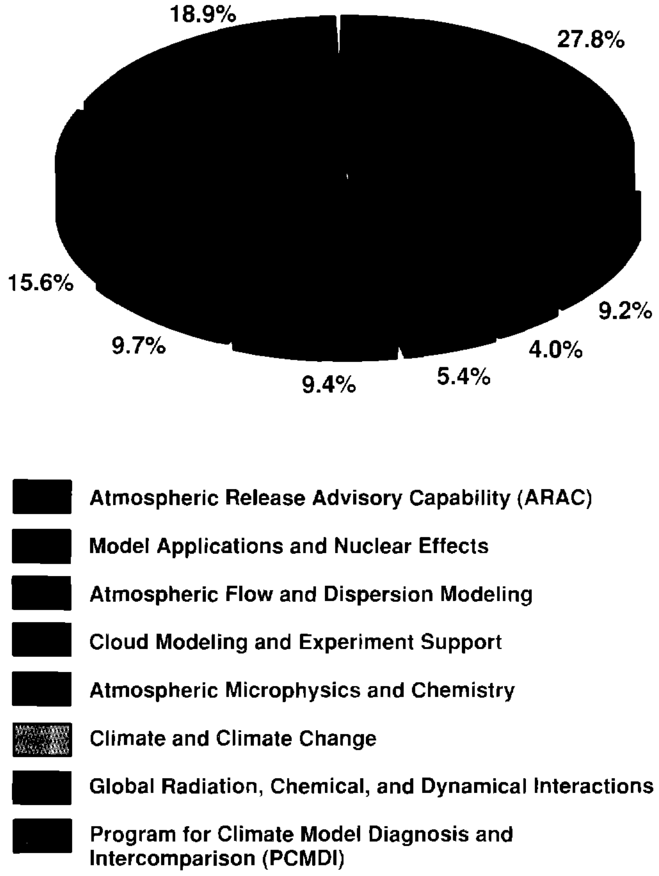

Figure 3. FY92 budget for each group in G-Division.

In a turn of events indicative of the changing times within the Laboratory, our AGS Program is now providing more funding support to scientists in the defense sciences program than their program is providing to us for traditional defense-related research studies. For example, several researchers in the defense sciences divisions are now participating in our expanding climate modeling programs.

Future Plans

As a result of our growth to meet the new challenges presented in 1990 and 1991, our program's capabilities are now significantly more comprehensive than several years ago. Both the global change and the accident preparedness, emergency response, and assessment areas are poised for further growth. As in the past, we will emphasize the development, verification, and application of comprehensive models of the atmosphere, ocean, and land system. In particular, we will concentrate on developing models capable of investigating perturbations to the system. We look forward to expanding our collaborative activities with the university community and with other laboratories. We believe that the scientific challenges faced by our country and the world can best be addressed through the combined efforts of joint and complementary research activities.

The growth of the program, while scientifically exciting, has put considerable strain on our facilities, particularly the Division's main office facilities. Although a new modular complex was built to house the PCMDI, many of our other groups are still housed in aging trailer complexes. Both short- and long-term measures have been initiated to resolve this situation. For the short-term, additional modular space is being made available by the Laboratory. For the long-term, the Laboratory has placed a new building for the Division, in particular for ARAC and related research activities, at the top of its construction list, and the DOE has included funding for this building in its proposed FY93 budget.

Historical Overview of the Atmospheric and Geophysical Sciences Program

The roots of the Atmospheric and Geophysical Sciences (AGS) Program at Lawrence Livermore National Laboratory (LLNL) can be traced back nearly to the establishment of the Laboratory forty years ago. We begin our historical overview with a brief look at the AGS research activities in the first decade following the Laboratory's founding in 1952. Next, we describe how our modeling capabilities were adapted and expanded to address the emerging environmental concerns of the late 1960s. Finally, we discuss the formation of LLNL's Atmospheric and Geophysical Sciences (G) Division nineteen years ago and its rapid growth in the 1970s and 1980s. This overview places special emphasis on the capabilities that have provided the basis for the current work and future plans of the AGS Program.

Taproots of the AGS Program

The two major focus areas of our present research program are rooted in the early history of AGS activities at the Laboratory. One focus area, modeling the global environment, grew out of the Laboratory's early use of supercomputers for numerical modeling. The other, preparing for and responding to the release of radionuclides and other hazardous materials, grew out of the Laboratory's environmental concerns for the safe conduct of nuclear tests and out of our research into the possible peaceful uses of nuclear explosives for large-scale engineering projects.

Modeling the Global Environment

From its beginning, the Laboratory has emphasized the use of computer simulations to augment experimental programs and theoretical studies. The earliest simulations were of weapons hydrodynamics and radiation transfer, for which the initial conditions (i.e., the structure of the device) are known and the main unknown is the overall power of the explosion; the calculation of this short-time, high-temperature event can be experimentally verified by testing. To further test capabilities for simulating nuclear-powered systems, related simulations were performed for stellar physics; these were generally steady-state calculations that could be tested by astronomical observations. The desire to harness fusion energy led to efforts to simulate the trapping of plasmas in magnetic fields; the intent was to design systems that were stable because development of wave instabilities prevents prolonged containment. A common thread through all of these early calculations at the Laboratory was the simulation of fluid flows and radiation (energy) transport. Thus, it was natural to attempt to simulate geophysical systems (i.e., the atmosphere and oceans), which are governed by similar physical relationships.

Attempting to calculate the Earth's geophysical systems was not a new effort. While he was an ambulance driver during World War I and without any modern computational tools, Lewis Richardson tried to calculate the evolution of the atmosphere by hand. His work was based on concepts first developed by Vihelm Bjerknes in the early 1900s (Bjerknes, 1920). In the late 1940s, John von Neumann and Joseph Smagorinsky, working at the Institute for Advanced Studies in Princeton, used some of the earliest computers to try and calculate the atmospheric circulation and evolution of the weather, albeit with highly simplified models. By the early 1960s, Smagorinsky had constructed a hemispheric general circulation model (GCM) based on the primitive form of the fundamental conservation equations, an achievement that provided the basis for establishing the Geophysical Fluid Dynamics Laboratory under the sponsorship of the National Oceanic and Atmospheric Administration.

With the encouragement of Edward Teller in the late 1950s, Cecil "Chuck" Leith (see box), whose background was in mathematics and weapons physics modeling, began a similar project at Livermore to simulate the global atmosphere. While on professional leave in

Cecil "Chuck" Leith

Cecil "Chuck" Leith joined the Livermore branch of the University of California Radiation Laboratory as a charter member in 1952. Chuck joined the Manhattan Project in 1943 following graduation from Berkeley, and worked both in Berkeley and Oak Ridge. Following World War II, he worked as an experimental high-energy physicist with Dr. Ernest Lawrence at the Radiation Laboratory in Berkeley. From 1946 to 1952, he co-authored papers with Lawrence, Emilio Segre, Herbert York (later Livermore's first director), and others. During his early days at Livermore, Chuck worked in numerical hydrodynamics, using then-primitive digital computer hardware to run nuclear design computer codes. In the midst of all this, Chuck earned his Ph.D. in Mathematics (1957) at the University of California, Berkeley.

In the late 1950s, Chuck turned his focus toward applying numerical methods developed for weapons physics to simulations of the global atmosphere. With his group, he developed the first global general circulation model in the early 1960s, and displayed the results in a movie that showed the model's weather as if one were looking at a global weather map from a satellite high above the North Pole. Chuck was also a founding faculty member of the University of California, Davis, Department of Applied Science (DAS) at Livermore. As envisioned by Edward Teller, this graduate department was to draw faculty largely from the Laboratory staff and to dedicate itself to training graduates who could span the gap between science and engineering.

The complexity of the observed atmospheric circulation compared to the relatively simple circulation simulated in his model led Chuck to tackle the problem of atmospheric turbulence, developing a new philosophical approach in conjunction with his DAS graduate students (in particular, George Nichol with whom he developed the concept of conservation of enstrophy). His students also included Monty Coffin, who modeled the climate of Mars; Mike MacCracken, who used Chuck's two-dimensional model to study theories of ice ages; and Greg Canavan, who modeled atmospheric turbulence.

In 1968, Chuck left Livermore for the National Center for Atmospheric Research, where he helped establish methods for the statistical analysis of atmospheric weather systems and made contributions in the areas of turbulence, predictability, and nonlinear normal-mode initialization. As head of the global modeling group, Chuck conceived the notion of the Community Climate Model and encouraged its early development. During these years, he contributed significantly to the planning of national and international research programs.

Chuck returned to Livermore in 1983 as a senior scientist, stimulating research in turbulent fluid dynamics in areas as diverse as fusion and weapons physics. His current research efforts focus on the use of massively parallel computers for simulation of fluid dynamic systems. Meanwhile, he continues in his advisory role to the atmospheric science programs at Livermore, the National Center for Atmospheric Research, the National Science Foundation, and other organizations. Chuck's official retirement from the Laboratory in [illegible] has not noticeably slowed him down; he continues to help others in their research and to venture into new areas, including satellite instrumentation.

Sweden in 1960, Leith coded the basic three-dimensional global evaluations to be run on the Livermore Advanced Research Computer (LARC). Leith's group, then called H-Group in the combined Physics and Computations Department, took on the task of expanding the model's capabilities. By the early 1960s, Leith and his team had constructed an atmospheric GCM (known as the Livermore Atmospheric Model, or LAM) that incorporated the diurnal cycle of solar and terrestrial radiation, predictive cloud cover, and convective and stratiform precipitation; some of these features were not incorporated into other GCMs *until the* 1980s. The group, which *initially included* Alex Cecil, Pat Crowley, John Hardy, Richard McLean, and Christine Sherman (later joined by John Walton, Hugh Ellsaesser, and several graduate students), were pioneers in the use of the LARC and IBM STRETCH computers. The group also made the first computer graphics 16-mm movie of the atmosphere, which even now, three decades later, provides interesting insights.

This successful modeling effort spawned a number of related projects and activities. Pat Crowley developed a three-dimensional ocean circulation model that generated a reasonable representation of oceanic gyres, although the model was too coarsely gridded to represent ocean eddies. John Hardy used LAM to understand the cause of the semidiurnal pressure wave at low latitudes, which showed up in the model as well as in observations, tracing it to the beating of the 24-hr rotation of the Earth against the 21-hr natural frequency of the atmosphere. George Nichol, a graduate student at the newly formed Livermore branch of the University of California's Department of Applied Science (DAS), examined the characteristics of large-scale atmospheric turbulence and the constraints imposed by the thin atmosphere, inventing the term "enstrophy" to describe the conservation of mean-square vorticity. Monty Coffin, another DAS graduate student, applied an early two-dimensional version of the atmospheric model to simulate the atmosphere of Mars, making predictions of what early satellites would later find (e.g., the carbon dioxide polar caps). Mike MacCracken, also a graduate student at DAS, transformed the two-dimensional version of the atmospheric model into a climate model and used it to simulate several hypotheses that were put forth to explain glacial cycling and, in particular, to estimate the shortcomings of a suggestion that an ice-free Arctic Ocean (then envisioned as a possible beneficial geoengineering transformation) would trigger an ice age.

The great enthusiasm resulting from the early successes in atmospheric modeling at the Laboratory and elsewhere was epitomized in a projection made in a 1965 report of the U.S. President's Science Advisory Council (PSAC, 1965) that, with the great advances in supercomputing and modeling, it would be only a few years before regional climate projections of carbon-dioxide-induced perturbations could be made. As it turned out, the climatic and nonlinear processes proved harder to calculate than anticipated. An early hint of this was evident in a satellite film loop that was shown in one of Leith's Friday afternoon team meetings, which contrasted the turbulent complexity of the real atmosphere with the rather placid model calculation. That stark difference spurred Leith to redirect much of his research attention on turbulence theory—perhaps as it had Lewis Richardson after his earlier effort to calculate the evolution of the atmosphere by hand.

In the late 1960s, Laboratory funding for such innovative research started to decline. Leith departed to the fledgling National Center for Atmospheric Research and his group largely dissipated, except for Hugh Ellsaesser and the newly hired Mike MacCracken, who both were reassigned to the Laboratory's Theoretical Physics (T) Division. It took the climate modeling program several years to again become a major effort at the Laboratory.

Simulating the Dispersion of Radionuclides from Peaceful Nuclear Explosions

At the same time that Leith was pursuing a global atmospheric model, atmospheric modeling of a different type was also being pursued in support of the Laboratory's Plowshare Program. This effort formed the second taproot of our current activities.

There will always be projects that are dreamed about but which seem beyond the capabilities of human endeavor. A whole class of these are projects that reconfigure the land surface. Projects that were actually considered in the late 1950s included construction of a sea-level canal across Central America, a canal across the Kra Peninsula (connecting Thailand and the Malaya Peninsula), a hydroelectric project involving a canal from the Mediterranean to the Qattara Depression (in Egypt), and various railroad passes through mountain ranges.

All of the above projects and others would require moving large amounts of dirt and rock. The Plowshare Program was begun in the 1950s to evaluate the feasibility of using nuclear explosives for this task. The engineering aspects—power and number of explosions, geometry of crater, and channel creation—were primary considerations of the Plowshare Program. Yet it was certainly realized that the injection of radionuclides into the atmosphere had to be minimized and that the effects of the spread and dispersal of any injected radionuclides had to be considered.

The issue of dispersal of radionuclides from atmospheric explosions of nuclear weapons had previously been addressed by the U.S. testing program, specifically by military and specially organized civilian weather-forecast teams. Atmospheric tests, generally performed at sites in remote areas, were capable of lofting radionuclides well into the atmosphere. Repeated tests allowed forecasters to learn from experience (some cases did indeed lead to unexpected results and off-site contamination). However, the situation was somewhat different for the proposed peaceful uses of nuclear explosives.

Joseph Knox (see box) was recruited in 1958 from the Department of Meteorology at the University of California, Los Angeles by the Laboratory to lead the

Joseph B. Knox

Joseph B. Knox, the first Division Leader of the Atmospheric and Geophysical Sciences (G) Division, began his thirty-year career at the Lawrence Livermore National Laboratory in 1958. Joe was both an undergraduate and a graduate in the Department of Meteorology, University of California, Los Angeles. Upon receiving his Ph.D. in 1955, Joe went on to teach in the Department, first as an Instructor and then as an Assistant Professor.

Three years later, Joe joined the then Lawrence Radiation Laboratory to develop the technical capabilities needed to simulate the cratering effects of nuclear explosives used for engineering projects and to model the dispersion and deposition of the radionuclides that would be lofted from such explosions. During this period, he served as Group Leader for [illegible] Physics in the Earth Sciences (K) Division, leading the evaluation of proposed [illegible] creation of a sea-level canal across Central America [illegible] and of the potential atmospheric consequences of a radionuclide release from the Amchitka Island underground test of the Spartan antiballistic missile warhead.

In the late 1960s and early 1970s, Joe became active in [illegible] for the Laboratory. He helped [illegible] the meteorological [illegible] for the [illegible] air quality [illegible] and for [illegible] of [illegible] exhaust [illegible] from the [illegible] of supersonic transport aircraft.

During a U.S. Department of Energy (DOE) review of the Laboratory's atmospheric program, Joe played his most important "acting" role. In a skit depicting a proposed Emergency Emissions Forecast Center, which he envisioned would be called on in the event of a nuclear reactor accident, Joe played the resident expert at the Center. He and Todd Crawford, who played the role of an environmental manager at a nuclear reactor site, were so convincing that the Laboratory's Atmospheric Release Advisory Capability (ARAC) was born.

During the early 1970s, the Laboratory's atmospheric modeling programs were consolidated into the Atmospheric and Geophysical Sciences (G) Division. Joe assumed leadership [illegible] promote the development of a wide range of research programs and activities, including [illegible] power siting, the [illegible] global change, and [illegible]. He served on national [illegible] numerous scientific papers [illegible] the Division's fine tradition [illegible] and the special [illegible] Division's founding.

Joe [illegible] in 1987. Being an [illegible] new challenge of [illegible] National Institute for [illegible] (NIGEC) at the University [illegible] its centers at six [illegible] the NIGEC supports [illegible] to the DOE's Carbon Dioxide Research Program.

program that was to develop the technical capabilities for simulating the injection, dispersal, and deposition of radionuclides from cratering explosives. Because the proposed projects would be of a scale well beyond the experience projected to be gained from the planned Plowshare test shots, the only means of estimating potential effects was through the use of numerical models of both the cratering and radionuclide dispersal components. This challenge became a major focus of what was then the Earth Sciences (K) Division in which Joe Knox was a Group Leader.

In the early 1960s, Knox's group included Todd Crawford, Len Lawson, and Howard Rodean, who all later became members of the Laboratory's atmospheric research program. They developed, tested, and verified the KDFOC code to calculate fallout from surface bursts and, similarly, the 2BPUFF code to calculate atmospheric dispersal of radionuclides from a number of proposed geoengineering projects. The most intense application of these codes was in support of the Sedan experiment, which took place in Nevada and generated a crater more than 370 m wide and 100 m deep.

When planning the experiment, dispersal models were used to calculate the potential concentrations of radionuclides and to allow experiment leaders to modify the scenario to assure that concentrations would be below specified limits when the radioactive cloud crossed U.S. borders. This was a requirement resulting from treaty negotiations with the former Soviet Union, in which Knox and Crawford had participated as invited technical experts.

A significant result of the Plowshare Program was the recognition of how effectively radioactive particles could be removed from the atmosphere by precipitation, a process called rainout. It became evident that rainout could create hot spots on the ground that could lead to high human doses of radiation either directly or through various food chains. The LLNL research team that studied this phenomena included Ted Harvey, Bob Perret, Chuck Molenkamp, Alan Williams, and Don Hardy as well as Joe Knox. Their results clearly indicated that nuclear weapons and cratering tests that could result in the atmospheric injection of radionuclides should be scheduled during periods having the least potential for rainout. Although this was possible for tests, it was realized that tactical nuclear warfare in Europe might well occur under rainy conditions and that tactical weapons, being of lower yield, would not generally loft the radionuclides above rain cloud and rainout altitudes. Estimates of potential dose levels to humans made it apparent that tactical warfare would create hostile environments for all forces involved. These findings contributed to a major long-term program to design nuclear weapons in such a way as to minimize radionuclide generation.

To extend the capabilities of Knox's group, Ken Peterson was recruited from the National Oceanic and Atmospheric Administration in the late 1960s to help estimate the regional- to global-scale transport of radionuclides released from both Plowshare scenarios and nuclear tests (including atmospheric nuclear tests by the French and Chinese). Win Crandall, a U.S. Air Force member on assignment to LLNL, also spent several years working on this project to calculate radionuclide deposition from nuclear tests and Plowshare experiments.

A culminating event in the group's activities was the test of the Spartan warhead, which was being designed for use on U.S. antiballistic missiles. This warhead's estimated yield of several megatons necessitated the movement of the test from the Nevada Test Site (NTS) to Amchitka Island in Alaska (our Trailer 1703 was reputedly one of those that made the trip there and back from NTS before being moved to LLNL). There was great concern that such a large test in a seismically active region might result in the accidental release of radionuclides, so extensive analyses were performed and, only with last minute approval by the U.S. Supreme Court, was the test successfully conducted in November 1971. Commissioner Thompson of the Atomic Energy Commission expressed appreciation for the environmental support efforts provided by Knox's group, wishing that the real-time capabilities developed to forecast potential releases from the Amchitka test could be available on a continuing basis for other activities involving actual or potential radionuclide releases. It was this request that formed the impetus for development of the Laboratory's Atmospheric Release Advisory Capability (ARAC) a few years later.

Responding to Increasing Environmental Awareness

During the late 1960s, increasing public concern about the environment, and an increasingly outward-looking perspective at the Laboratory, together led to three new projects, each aimed at applying our atmospheric modeling capabilities to regional and national environmental issues. These issues included (1) the rising level of ozone exceedances in the San Francisco Bay Area, (2) the potential environmental effects of the proposed fleet of supersonic transport aircraft, and (3) the threat of radionuclide releases from nuclear facilities.

Modeling Air Quality

An ozone air-quality station was opened in downtown Livermore in the late 1960s, and measurements taken over the first few years suggested a strong upward trend in the number of violations of the air-quality standard. (Whether this was really a trend or simply year-to-year fluctuations was never really clarified.) The City of Livermore Air Pollution Control Study Committee, chaired by Todd Crawford, attributed about half of the problem to local emissions and about half to air pollution coming in from the central Bay Area; clearly the problem required a regional perspective.

The rising environmental concern at both local and national levels that was associated with these events led Laboratory Director Roger Batzel to form a Laboratory environmental committee, led by Carroll Maninger, Todd Crawford, and James Kane, to consider what the Laboratory could do in response to growing concerns about air pollution. One recommendation was to develop a simulation capability. Mike MacCracken (challenged by a doughnut bet with Hugh Ellsaesser) began development of a regional air-quality model; Joe Knox, Todd Crawford, and Ken Peterson provided extensive meteorological data, and Alan Hindmarsh provided a new chemical equation solver. MacCracken also developed a mass-consistent wind-field model to drive the air-quality model. Simultaneously, Robert Gelinas, who was also in T-Division, began using the Gear technique (Gear, 1971) to solve the set of atmospheric chemistry reactions determining regional ozone concentrations. These two efforts later merged to become the Livermore Regional Air Quality (LIRAQ) model.

Fortuitously, Norman Bonner, a Laboratory chemist, was serving as an expert on the advisory panel of the Bay Area Air Quality Management District (BAAQMD), then named the Bay Area Air Pollution Control District. Bonner offered to have Todd Crawford and Mike MacCracken speak to the Board of Directors about an exploratory project at the Laboratory to model the region's air quality. The subsequent interest of the BAAQMD staff led to a three-agency project to develop and verify a comprehensive regional air-quality model. The project participants included the BAAQMD, LLNL, and the NASA/Ames Research Center in Mountain View, California. The project was funded by the National Science Foundation's Research Applied to National Needs program. The BAAQMD staff provided the emissions and meteorological data, the LLNL team developed and tested the model, and the scientists at the Ames Research Center flew their aircraft to provide measurements of air pollutant concentrations aloft. At LLNL, Ted Stullich was an early contributor to this project; later joined by Marv Dickerson, Bill Duewer, Keith Grant, and Don Wuebbles.

During the mid and late 1970s, the LIRAQ model was used to develop the BAAQMD's ozone air-quality maintenance plan, which emphasized, based on model results, stringent controls of reactive hydrocarbons. The plan's basic strategy has been followed ever since, and the reduction in hydrocarbon emissions in the Bay Area (e.g., via gasoline fuel-recovery valves and water-based paints) has, it is believed, contributed to the significant reduction in exceedances of the federal ozone air-quality standard. A later application of the model to study the air quality in St. Louis, Missouri was carried out by Joyce Penner.

Modeling the Climatic Effects of Supersonic Transport Aircraft

Another Laboratory project that addressed the environmental concerns of the 1960s was a study to assess the climatic effects of supersonic transport (SST) aircraft. The climate modeling capabilities at the Laboratory attracted a visit from Alan Grobecker and Sam Coroniti of the U.S. Department of Transportation's (DOT) Climatic Impact Assessment Program, which resulted in a project to evaluate the potential plume-mixing, chemical, and climatic effects of a proposed fleet of SST aircraft.

Responsibility for simulating the dispersion of aircraft exhaust plumes was assigned primarily to scientists in K-Division, who had experience in modeling the spread of radionuclide clouds. In addition, John Walton returned to T-Division from an assignment in the Magnetic Fusion Energy program to work on this aspect and was later joined by Bill Moreland. The chemistry modeling effort drew from the capabilities being developed for the air-quality modeling project previously described; Julius Chang returned to the Laboratory from the State University of New York at Stony Brook to lead this part of the effort and was joined by Don Wuebbles and Bill Duewer in these studies. The climate modeling effort was based on Mike MacCracken's two-dimensional climate model; Jerry Potter later joined this effort. Fred Luther, a 1969 DAS graduate who had gone on to teach physics at the U.S. Naval Academy for a few years, rejoined the Laboratory to work on the radiation aspects of the climate model.

Calculations carried out during the course of this project led to several interesting scientific results. Simulations indicated that nitrogen oxide emissions from the exhausts of the SST aircraft could reduce stratospheric ozone levels by several percent. Calculations using atmospheric radiation models predicted that such a reduction in stratospheric ozone would lead to an increase in ultraviolet radiation at the Earth's surface. Calculations using our two-dimensional climate model indicated that the sulfur oxide emissions could create a volcanic-like veil of sulfate aerosols that would tend to cool the global climate slightly. These findings on the potentially damaging environmental effects from SSTs contributed to the environmental assessment that ended the nation's SST development program.

Modeling the Accidental Release of Radionuclides

During the early 1970s, the Laboratory addressed a third environmental issue: the threat of radionuclide releases from nuclear facilities. The conceptual design of an Emergency Emissions Forecast Center (EEFC) had emerged following the Amchitka Island experience previously discussed. The need for such a center to provide such expanded capabilities was considered at a review of the Laboratory's atmospheric sciences program by the U.S. Department of Energy's (DOE) Office of Health and Environmental Research. During this review, a skit was used to illustrate how such a center might work. Todd Crawford played the role of an environmental manager at a nuclear reactor site where an emergency situation was developing. Joe Knox played the role of an expert at an imagined EEFC, providing the manager with information on the potential consequences of a release of radionuclides. The response was generally very positive; the reviewers liked the idea of a modeling center, but were not enthusiastic about the implications inherent in the proposed center's name—radionuclides, emergency, release. One of the reviewers, Robert Catlin from the Electric Power Research Institute, suggested what later became the name, the Atmospheric Release Advisory Capability.

Under the initial leadership of Joe Knox, a number of scientists were involved in getting the ARAC project started. Marv Dickerson joined the Laboratory from Florida State University, where he had worked as a teaching and research assistant. Dickerson's first assignment (later with help from Phil Gresho) was to provide a more solid mathematical basis for the mass-consistent wind-field model that had been developed for the Bay Area modeling project. Dickerson eventually led ARAC project development; Christine Sherman transformed the wind field model to three dimensions; Rolf Lange, assisted by Len Lawson, created an atmospheric dispersion particle-in-cell model; Chuck Veith assembled the necessary meteorological data; and Rick Pollack provided statistical support.

An initial task of the ARAC project was to evaluate the capability of these models to simulate pollutant dispersion on local-to-continental spatial scales. In one of the studies to evaluate and improve model performance, Dan Rodriguez, who joined the ARAC model development team during the mid-1970s, used data from several field tracer experiments to evaluate model performance. These experiments included data from local-scale tracer releases at the Savannah River Plant, regional-scale trace trajectories over the northeastern states, and continental-scale tracer transport across the United States. Betty Jankus joined ARAC to help with air-quality assessments, before later joining the U.S. Environmental Protection Agency.

Understanding the Consequences of Atmospheric Perturbations

With the emerging environmental movement of the early 1970s and atmospheric research activities spread between T-Division, which was in the Physics Department and led then by Wilson Talley, and K-Division, which was administered by Defense Programs and led then by Jack Kahn, there was clearly a need for an organizational merger. With the encouragement of Todd Crawford, who was leaving the Laboratory to direct the environmental research program at the Savannah River Laboratory, Director Roger Batzel announced the formation of G-Group, led by Joe Knox and located organizationally within the Physics Department. A total of about twenty staff members from T- and K-Divisions were transferred to G-Group in 1973. We first moved into the trailer complex still standing to the south of Bldg. 131 and then, in 1977, we moved into an aging trailer complex (that was abandoned by the Laser Program) in the 1700 block at the Laboratory. It is still our home. The complex was soon dubbed "the orphanage" in honor of Dick Orphan, who bore the administrative responsibility for the group. To provide secretarial support, Carol Myers, who was Joe Knox's former secretary in K-Division, joined G-Group. She was soon joined by Floy Worden, a secretary with previous experience in the Physics Department.

In March 1974, G-Group became G-Division. Joe Knox, as Division Leader, was assigned responsibility for the AGS Program at the Laboratory. Knox continued to serve until his retirement in October 1987, by which time the Program's staff had grown to about 80 members; we are now at almost 150!

The joining of K- and T-Divisions strengthened and benefited both programs. The scope of G-Division's activities grew to include the simulation, evaluation, and assessment of many different emissions into the environment. The Division continued to focus on the early research directions set in the AGS Program. The following subsections describe some of our significant projects during the 1970s and 1980s in the areas of climate and atmospheric chemistry, and of regional modeling.

Climate and Atmospheric Chemistry

Our research in the area of global change grew out of our early projects in support of the supersonic transport and the Bay Area air-quality modeling projects. New challenges arose that led to major new projects, a few of which are described below.

Stratospheric Ozone Depletion

A major new project in the mid-1970s was the study of the consequences of a nuclear war on stratospheric ozone and climate. This project had been prompted by a keypunching error during a simulation to emulate the effects of nuclear testing on stratospheric ozone; Julius Chang accidentally ran an explosive yield calculation 1000 times higher than that of a nuclear test, and this calculation showed that under these conditions the ozone layer would be nearly destroyed. Chang realized that he had just simulated the potential effects of a nuclear war. From this accidental calculation, the Strategic War project was born, and a National Academy of Sciences study ensued to evaluate the effects of nuclear war on atmospheric chemistry and climate. This study reinforced the need to move away from very high-yield weapons to avoid the threat of severe ozone depletion following a nuclear war.

Although the Climatic Impact Assessment Program ended in 1974, we participated until 1980 in a follow-up program sponsored by the DOT's High Altitude Pollution Program to investigate the potential environmental effects of subsonic and supersonic aircraft on the ozone layer. Throughout the 1970s, a one-dimensional model was the main tool used in the analysis of stratospheric chemistry. Current analyses use a zonally averaged, two-dimensional model, and we are presently developing a three-dimensional model for studies of global atmospheric chemistry.

In addition to concerns about the environmental effects of supersonic aircraft and nuclear war on the ozone layer, interest arose in 1974 regarding the potential effects on stratospheric ozone from emissions of chlorofluorocarbons (CFCs). We soon began to apply our models to the study of CFC effects on ozone. In 1981, Don Wuebbles developed the concept of ozone depletion potential, which was later used by national and international policymakers as a basis for limiting the production of CFCs and other compounds that affect ozone. Following the accidental death of Bill Duewer, Peter Connell joined us in the early 1980s to participate in these research studies.

Our interest in the potential depletion of the ozone layer led to Jim Lovill, who was just out of the U.S. Air Force, joining the Group in 1973. Tom Sullivan, also from the U.S. Air Force, joined Lovill in 1974. In addition to providing Dickerson's newly born ARAC project with meteorological support, Sullivan worked with Lovill on a series of ozone analysis studies culminating in the formation of the Satellite Ozone Analysis Center (SOAC), funded by the DOT and Federal Aviation Administration. This project used data from the infrared sounder that was launched as part of the Defense Meteorological Satellite Program to fill a three year gap (1978–81) in NASA's nearly decade-long Nimbus ozone measurement effort. The SOAC project later attracted John Korver, Roger Weichel, Jim Ellis, and Stan Grotch to the Division. In addition, Fred Luther contributed both radiative transfer and management support to the project. The SOAC team generated some of the first daily maps of the global distribution of total stratospheric ozone; they also successfully linked the ozone measurement record between the Nimbus Infrared Interferometer Spectrometer and Solar Backscatter Ultra-Violet satellite measurement programs.

Carbon Dioxide and Climate

A letter from Mike MacCracken to Rudy Englemann in 1975 played a role in encouraging the U.S. Energy Research and Development Administration (ERDA), and then the DOE, to organize the nation's first focused research program on the potential climatic effects of carbon dioxide and other greenhouse gases. Although there was concern in the early 1970s that cooling might prevail as a result of aerosol contributions from human activities, MacCracken's letter presented the case for an enhanced greenhouse effect. DOE staff circulated the letter to an international set of experts for comment and, as a result of the experts' reactions, organized a workshop in 1977 to design a research program. When this DOE program started, LLNL became part of the research team.

The Laboratory's carbon dioxide research program grew from this beginning to include a broad array of climate modeling projects. One such project was an intercomparison of infrared and solar radiation codes, led by Fred Luther with help from Jim Ellis, which quantified the uncertainty in the models and pointed to the need for the DOE's current Atmospheric Radiation Measurement (ARM) program. Our modeling studies were also expanded to include the effects of trace gases on climate, an effort led by Don Wuebbles, and later the effects of aerosols on climate, led by Joyce Penner. Early in the program, Jerry Potter, Jim Ellis, Hugh Ellsaesser, and Fred Luther worked with Mike MacCracken to carry out a number of carbon dioxide sensitivity experiments with our two-dimensional climate model as a follow-on to the Climatic Impact Assessment Program. In addition, studies of the potential climatic effects of tropical deforestation, desertification, extensive use of solar collectors, and other possible changes were conducted. Jerry also initiated some innovative model analysis studies, working with Connee (Mitchell) Foster, who joined G-Division as a student employee. Jerry also became our first Division member to participate in the U.S.-U.S.S.R. Working Group VIII activities, establishing a number of collaborative efforts in climate modeling. Mike MacCracken and Don Wuebbles later also participated in Working Group VIII activities, with MacCracken succeeding Larry Gates and serving as the U.S. co-chairman from 1984 to 1990.

To move beyond two-dimensional climate modeling studies, Jerry Potter initiated a collaboration with Larry Gates of Oregon State University (OSU) using the three-dimensional OSU GCM. Studies with this model, some done in collaboration with Robert Cess of the State University of New York at Stony Brook, pointed to the weaknesses and sensitivities in GCMs. These weaknesses also became evident in the DOE state-of-the-art reviews on climate projection and climate change detection prepared in 1984–85 under the editorship of Mike MacCracken and Fred Luther (MacCracken and Luther, 1985a,b).

The disagreements among the GCM results led DOE to ask that a program be developed to determine the causes of these differences. Early studies provided important insight into the significant uncertainties introduced by clouds and their interactions with radiation. Those disagreements that became evident reinforced an earlier call by Larry Gates for the systematic intercomparison of climate models. He was asked to lead this effort and joined the Laboratory as Director of the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The PCMDI now conducts model verification studies and leads model comparison projects involving many research groups from around the world.

Environmental Consequences of Nuclear War

Another major project that grew out of our early climate and atmospheric chemistry research was the study of the global environmental effects of nuclear war. Just as the threat of ozone depletion became an overriding concern in the mid-1970s, the potential for severe climatic effects from the dark clouds of smoke that would be generated by the thousands of fires ignited in the event of a nuclear war became the environmental threat of most concern in the 1980s. Even before publication of the paper dubbing this effect "nuclear winter" (Turco et al., 1983), we were applying our two-dimensional climate model to this problem and had assigned John Walton to work on developing the three-dimensional GRANTOUR smoke transport model. Fred Luther applied radiation transport models to estimate the effects of smoke emissions on solar radiation. The three-dimensional OSU climate model was also used early on by Jerry Potter, Robert Cess, and Larry Gates to improve understanding of the sensitivity of the climate response to smoke optical depth and altitude. This project quickly became a Director's Initiative, a special project sponsored by the Laboratory Director. Our research included the study of nuclear scenarios, fire spread, smoke cloud development and scavenging, fallout, and climatic and chemical effects. These diverse efforts were led by Mike MacCracken and Joyce Penner. Mike Bradley, Les Edwards, Steve Ghan, Ted Harvey, Charles Shapiro, and others from across the Laboratory joined the G-Division staff to carry out these studies.

Regional Modeling

Regional modeling, a major thrust of the Division's activities in the 1970s and 1980s, also arose from the original research efforts of the AGS Program. The organization of the ARAC project in the mid-1970s, which involved both extensive modeling and computational aspects, brought George Greenly and Dan Rodriguez to the Laboratory and Paul Gudiksen to the program to lead assessment activities. Don Hardy, Christine Sherman, and Bill Porch took the ARAC tools and, with Joe Knox, used them to identify suitable wind power sites in both Hawaii and in the Bay Area.

Accidental Release of Radionuclides

By 1979, several DOE facilities were receiving the ARAC emergency response service (Rocky Flats Plant, Mound Laboratory, Savannah River Plant, and LLNL). At the same time that the DOE was evaluating the operations of ARAC and deciding on funding support for continued operation, the accident at the Three Mile Island (TMI) nuclear power plant in Pennsylvania occurred (March 27, 1979). ARAC operated 24-hr-per-day for a month, providing the emergency response managers at TMI with the projected radiation dose to the public and with data that could be used for planning aircraft and ground measurement missions. ARAC's contribution to the health effects assessment both during and after the accident proved that ARAC would be a valuable aid for emergency response managers. Nearly the entire Division supported ARAC during TMI. The leaders of the effort included Christine Sherman, who supervised the center; Marv Dickerson and Paul Gudiksen, who rotated serving as the ARAC on-site representative in Harrisburg, Pennsylvania; Tom Sullivan, Jim Ellis, Roger Weichel, and Hugh Ellsaesser, who became interim ARAC meteorologists; Ken Peterson, Dan Rodriguez, Len Lawson and Rolf Lange, who manipulated the models; Floy Worden, who input much of the data; and the engineering staff, who handled the ARAC computers. In addition, the Laboratory's Hazards Control Department provided several health physicists for dose consequence support.

Following the TMI accident, the number of ARAC staff was increased so they could provide continuing service to the U.S. Department of Defense and the Nuclear Regulatory Commission, as well as the DOE. The new staff members included Connee (Mitchell) Foster, Kevin Foster, and additional meteorological and computational support staff from EG&G. Since TMI, ARAC has provided emergency response assistance for a wide range of accidents and potential accidents. These have included the U.S.S.R. Cosmos nuclear-powered satellite reentries and the Chernobyl nuclear reactor accident. More recently, ARAC has helped track smoke plumes resulting from the Kuwaiti oil fires and the ash plumes generated by the Mt. Pinatubo volcanic eruption.

The ARAC project also initiated an advanced model research and development effort that included Phil Gresho, Stevens Chan, Bob Lee, John Leone, consultant Bob Sani, and computer scientist Craig Upson. The objective of the effort was to develop dynamic regional flow models that would be able to aid ARAC in predicting the evolution of the mesoscale weather and the dispersal of pollutants. The focus of this effort has been on using finite-element methods (FEMs) to account for complex topographic interactions. Although the specialized computers used by ARAC to achieve real-time access and response have not been fast enough to use these models, this effort has led to several advances that have attracted international attention, including some pioneering contributions in the application of FEMs for studying fluid flows. In addition to their work related to the atmospheric boundary layer (ABL), there has been a continuing series of non-ABL projects that have involved (a) applying the FEM Boussinesq code to the thermal convection flow of liquid uranium in the melt to help the LLNL Atomic Vapor Laser Isotope Separation project scientists understand the basic fluid mechanics in their new isotope separation technique; (b) studying the complex, buoyancy-induced thermal convection occurring in the wing tanks of fighter aircraft, thus helping NASA/Langley to determine "time to freezing" of advanced fuels; and (c) applying FEM techniques to the simulation of electricity and magnetism—first for the time-dependent Maxwell curl equation (for the LLNL Engineering Department) and later for the problem of the induction heating of a metal crucible used for growing pure crystals (for the LLNL Laser Program).

Emissions from Alternative Energy Systems

During the mid-1970s, the DOE focused on the development of alternative energy technologies in support of Project Independence, an effort to wean the U.S. off of imported oil. Because many regions within the western U.S. have significant geothermal resources, the DOE was interested in supporting the development of the technology needed to use these resources for electric power production. Tapping into these energy sources, however, has the potential of producing significant environmental impacts. Developing the geothermal energy resources within the Imperial Valley in southern California was of particular interest to the DOE. The DOE asked the Laboratory to lead a major study to evaluate the potential impacts of various energy development scenarios. This project, named the Imperial Valley Environmental Project (IVEP), was headed by Lynn Anspaugh and Paul Phelps of the Laboratory's Environmental Sciences Division. Paul Gudiksen was asked to manage the air-quality-impact component of this project; he was assisted by Don Ermak, Ken Lamson, and Don Garka. This study required both field experiments and atmospheric modeling studies to evaluate the expected change in the air quality within the Imperial Valley due to the generation of several thousand megawatts of electrical power from the extensive hot-water geothermal resources. The study included the analyzing of geothermal fluids to estimate the amount of noxious gases that would be released, the taking of air-quality and meteorological measurements to characterize the current air quality and the dispersion capability of the atmosphere within the Imperial Valley, and numerical modeling using our models to derive pollutant concentrations.

On completion of the IVEP, we began to investigate the feasibility of performing similar studies in The Geysers, a geothermal area located in the mountainous Coastal Range north of San Francisco, California and tapped into by Pacific Gas and Electric to generate electric power. This area was chosen because hydrogen sulfide emissions had caused an impact on the regional air quality. It quickly became apparent that available atmospheric dispersion models were inadequate for simulating the physical processes responsible for pollutant transport in an area of such complex terrain. This, among other factors, led the DOE in 1978 to initiate the Atmospheric Studies in Complex Terrain (ASCOT), a multilaboratory program to study atmospheric boundary-layer behavior over complex terrain. We were active in the ASCOT program, providing initial leadership and participating in field experiments and in numerical model development and evaluation. Marv Dickerson was selected as ASCOT Scientific Director and Paul Gudiksen as the Experimental Field Program Manager. The Laboratory's field-experiment support team included Bill Porch, Ken Lamson, Don Garka, and Pat Ellis; and the numerical modeling team included John Leone, Phil Gresho, Bob Lee, Rolf Lange, and Len Lawson.

Model Validation Using Tracer Experiments

During the early 1970s, Joe Knox was asked to serve on the U.S. Air Force Technical Applications Center (AFTAC) advisory panel. One of AFTAC's interests at that time was to evaluate the accuracy of various types of models for simulating pollutant dispersion over distances of several tens of kilometers. In view of this interest, the AFTAC funded several tracer experiments at the Savannah River Plant for model evaluation purposes during the late 1970s. We were asked to use the results of these experiments to evaluate our MATHEW (a mass-conservation wind-field code) and ADPIC (a Lagrangian particle advection-diffusion code) models. The AFTAC also provided support to some of our ASCOT-related model evaluation studies because several of their sites of interest were located in areas of complex terrain. During the 1980s, the AFTAC's interests grew to include studying the transport of pollutants on a continental-to-global scale. To test our models at these scales, we used them to simulate the transport and dispersion of material released as part of the Across North America Tracer Experiment (ANATEX).

Releases of Heavier-than-Air Gases

In the 1970s, there was an increased interest in using liquefied natural gas (LNG). Because LNG is so cold, accidental releases of it would produce denser-than-air gas accumulations, forming "clouds" that stay near the ground and become trapped in low spots and valleys, thereby creating potentially explosive situations. To better understand the physics of such phenomena, the Laboratory established a major experimental and modeling program (J-Program) in 1978; it was led initially by William Hogan and then by Ron Koopman and Don Ermak. Our finite-element modeling team contributed to this program by developing a new three-dimensional, finite-element, conservation equation model (FEM3) based on the nonhydrostatic generalized anelastic equations. They also generated a hydrostatic model, but discarded it when tests against data from field experiments proved that such a model was less than generally applicable. FEM3's development and model evaluation with field-scale test results were conducted by Stevens Chan through the mid-1980s, and the one-dimensional, vertically averaged, conservation equation model (SLAB) was developed by Don Ermak. Both models are used by industry and have earned the reputation of being among the best in their respective class of models for simulating dense-gas-dispersion scenarios.

With the closing down of the experimental program, the modeling component of this program was assigned to G-Division in 1987, bringing Don Ermak, Ron Koopman, and Howard Rodean into the Division. Ron Koopman has since moved on to the Energy Program, while Don Ermak continues to lead modeling studies of toxic and heavier-than-air gases. Howard Rodean turned his interests to turbulence in the ambient atmosphere and began work on a stochastic turbulence model. Since the merger, modeling efforts in this area have focused on (1) developing the ability to simulate more realistic (and more complicated) release scenarios, including flow and dispersion within and around structures, and (2) modifying the ADPIC advection-diffusion model to treat cold, dense-gas dispersion.

Acid Precipitation

As the Atomic Energy Commission became the ERDA, it assumed broader energy responsibilities and a broader set of environmental problems. When the ERDA's Multistate Atmospheric Power Production Pollution Study (MAP3S) took on the investigation of sulfur pollution and acid deposition in the eastern U.S., Dave Slade of ERDA recruited Mike MacCracken to lead the MAP3S and to coordinate a program involving Argonne National Laboratory, Brookhaven National Laboratory, Pacific Northwest Laboratory, and a number of university research groups. MacCracken led the program from 1975 to 1978 at which time the program was transferred to the U.S. Environmental Protection Agency. This program later formed the basis for the National Acid Precipitation Assessment Program (NAPAP), and Julius Chang was eventually recruited to the National Center for Atmospheric Research from LLNL to lead the NAPAP modeling program. MacCracken is now serving as chairman of a U.S.-Canada panel evaluating acid rain model verification against field experiments, a carryover from this earlier project.

Summary

Once barely a blip on the Laboratory's budget, the ACS Program now represents about 2% of the overall budget. As we have evolved from the original programs and talents of the Laboratory, we have continued to focus on global modeling and accident preparedness and emergency response, but we are now playing an increasingly visible role in national and international environmental research programs. Our global modeling studies are moving toward simulation of the coupled atmosphere-ocean-land-biosphere system, with projects ranging from model intercomparison and analysis to model development and evaluation. On the regional scale, we are providing real-time support to emergency response managers in the event of a threatened or accidental release of radionculides and other materials while also carrying out assessments of past releases and developing capabilities to make even more accurate predictions. It is the development of these complementary capabilities over the past three decades that provides the foundation for our present and future contributions.

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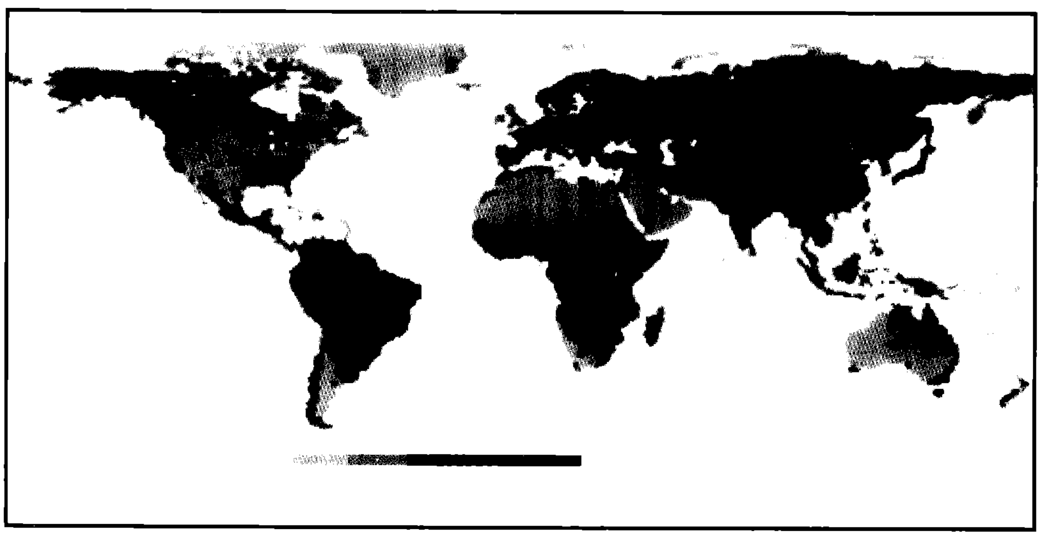
Section 2



Simulation of Global Nitrogen Oxide Emissions from Biomass Burning

Nitrogen oxides (NO_x) are primary pollutants that contribute to photochemical smog and acid rain. NO_x is emitted into the atmosphere by a number of natural and anthropogenic sources, including the burning of biomass (e.g., forests, grasslands, and agricultural wastes). We have developed a gridded global inventory of the emissions of NO_x from biomass burning using estimates of the amount of biomass burned in each region together with estimates of the dominant type of vegetation and its nitrogen content. Worldwide estimates of annual NO_x (g N m^{-2}) emissions from biomass burning are shown here on a 1° latitude by 1° longitude grid map, with the highest levels of emissions (orange and red) appearing in the regions of savanna/grassland in Africa and South America, and in the rain forests of Southeast Asia, southern Brazil, and Central America. These results indicate that the total annual emission rate (~13 Tg N) is nearly twice as high as previous inventories.

Assessing the Real-Time Atmospheric Effects of Hazardous Material Releases on Local, Regional, and Global Scales

Thomas J. Sullivan, Program Director

The Atmospheric Release Advisory Capability (ARAC) Group maintains a centralized system for assessing atmospheric releases of hazardous materials in real time. We recently responded to the oil fires in Kuwait, the eruptions of Mt. Pinatubo, and the toxic spill in Lake Shasta.

The ARAC group is responsible to the U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD), and other federal agencies under the auspices of the Federal Radiological Emergency Response Plan for developing and providing real-time assessments of the consequences of atmospheric dispersion and deposition of radionuclides in the event of potential or accidental releases of radioactive material into the atmosphere. Within the DOE Emergency Preparedness and Response Program, ARAC provides direct support to all of this program's specialized elements (i.e., the Nuclear Emergency Search Team, the Accident Response Group, the Federal Radiological Monitoring and Assessment Center, and the Radiological Assistance Program). Direct support includes:

• Providing immediate initial-response dispersal assessments.

• Supplying continuous updates and projections throughout the emergency (including 24-hr-per-day operation).

• When appropriate, sending an ARAC assessor to the coordination center at the scene of the emergency.

ARAC also serves as a key emergency preparedness training resource for nearly 50 individual DOD and DOE facilities and provides the major assessment capability for the Nuclear Regulatory Commission, the Environmental Protection Agency, and the Federal Aviation Administration whenever radioactive material is released into the atmosphere. Internationally, the United Kingdom's Atomic Weapons Establishment has arranged for ARAC assessment support for radiological incidents in the United Kingdom, and both the International Atomic Energy Agency and the World Meteorological Organization have at times requested ARAC's assistance through DOE headquarters.

Program Sponsorship History

The original ARAC concept, prototype development, and initial operations from 1972–79 were funded by DOE's Office of Health and Environmental Research. In 1979, the Office of Nuclear Safety assumed program sponsorship. The DOD funded a major expansion entailing redesign and increased automation from 1983 through 1986 to increase the project's capabilities from 10 to 100 sites. In 1987, a Memorandum of Understanding was negotiated between DOE and DOD providing for equal operational cost-sharing to support 40-hr-per-week "immediate" and off-hours "as available" response service for the 50 designated sites then supported. In 1988, the Naval Reactors Program added 20 sites on a cost-sharing basis, increasing the total site count to 70. In mid-1990, ARAC was transferred (within DOE) from Environment and Health to the Defense Programs Office of Military Applications. Beginning in 1992, the number of DOD facilities supported by ARAC was reduced as DOD restructured following the end of the Cold War era.

Recent ARAC funding totals \$4–4.5 M from all sources; these funds support a staff of 24–28 scientific, engineering, and computational operations personnel, a VAX-based computer system, and all of the data/communications requirements of the service.

Response to Technological Accidents

Since the beginning of operations in 1974, ARAC has participated in over 600 responses, consisting primarily of exercises with the agencies it supports. Previous reports describe ARAC's models, sources of atmospheric data, communications, and graphics tools and show how these components are integrated into a real-time emergency-response system for assessing atmospheric hazards (Sherman, 1978; Lange, 1978; Knox et al., 1981; Dickerson et al., 1983; U.S. Nuclear Regulatory Commission, 1986; Gudiksen et al., 1986; LLNL, 1987 Walker, 1984; Walker, 1989; Foster and Dickerson, 1990; Sullivan, 1989; LLNL, 1990). In accordance with its charter, ARAC has been used to model major domestic radiological events and some international events in which the U.S. government had an interest. In addition, as Table 1 indicates, ARAC has also been asked to respond to a number of nonradiological releases within the United States. In fact, requests for assistance involving nonradiological releases have equaled those involving radioactive releases. Our ARAC staff can provide an initial assessment of radiological accidents within less than

Table 1. Notable ARAC responses.

Year	Location	Source	Release
1976	North Carolina	Train accident	Uranium hexafluoride[a]
1978	Northern Canada	Cosmos-954 reentry	Fission products
1979	Three Mile Island Harrisburg, Pennsylvania	Nuclear power plant	Mixed fission products
1980	Damascus, Arkansas	Titan II missile	Missile fuel[a]
1981	Indian Ocean	Cosmos-1402 reentry	Fission products
1982	South Carolina	Savannah River plant	Hydrogen sulfide leak[a]
1986	Gore, Oklahoma	Sequoyah Fuels plant	Uranium hexafluoride[a]
1986	Chernobyl, U.S.S.R.	Nuclear power plant	Mixed fission products
1988	Miamisburg, Ohio	Mound plant	Tritium gas release
1989	Amarillo, Texas	Pantex plant	Tritium gas release
1991	Persian Gulf	Nuclear facilities Kuwaiti oil fires Missile warheads	Mixed fission products Smoke[a] Chemical agents[a]
1991	Philippines	Mt. Pinatubo	Volcanic ash[a]
1991	Northern California	Railroad car spill	Toxic gas products[a]

[a]Release involved toxic chemicals

30 min during normal work hours; at all other times, an on-call staff can make an initial assessment response within 90 min. As a result of our success in responding to and simulating radioactive atmospheric release accidents throughout the world, ARAC has received international recognition and acceptance. We have provided our primary models and/or various consulting services to Brazil, India, Israel, Italy, Japan, Korea, Spain, Sweden, the Federal Republic of Germany, and the United Kingdom.

Our current ARAC system evolved in two ways: by developing capabilities that met the initial requirements and expectations of the agencies that it supports and by incorporating new capabilities that have been identified as necessary during actual responses (Knox et al., 1981; Gudiksen et al., 1986; Sullivan, 1988; Sullivan, 1989). For example, early in the history of ARAC, a 1976 North Carolina train accident revealed that the availability of real-time meteorological data was essential to a rapid response. In 1978, a unique request by DOE to estimate the atmospheric consequences of the reentry of the Russian nuclear-powered Cosmos-954 satellite led the ARAC team to implement a high-altitude particle-fall model. As a result, we were prepared to assess the subsequent Cosmos-1402 reentry in 1981. Our largely manual responses to the 1979 Three Mile Island accident and the 1980 Titan II missile accident showed that the real-time meteorological data needed to be automatically formatted for use in the dispersion models and that on-line topographic and geographic data bases were required. The 1986 Chernobyl accident propelled us to implement continental-to-hemispheric scale models supported by worldwide meteorological, terrain, and mapping data. The knowledge gained during each new response has resulted in an expansion of ARAC's capabilities. Recent examples of the usefulness of our current capabilities are illustrated in our responses to the Persian Gulf crisis, the eruption of the Mt. Pinatubo in the Philippines, and the herbicide spill that affected California's Upper Sacramento River and the Lake Shasta reservoir. Each of these responses is described in the following sections.

Persian Gulf Responses

The year 1991 was the most demanding year experienced by the ARAC group. At 1520 PST on the afternoon of January 16, 1991, just minutes after Coalition Forces began the air war signaling the start of Operation Desert Storm in the Persian Gulf, ARAC's scientists received the first of several urgent requests from the DOE's Emergency Operations Center (EOC). We were asked to provide immediate assistance in assessing the possible consequences of events triggered by Operation Desert Storm.

The first request from the EOC was to evaluate the hypothetical dispersal of chemical warfare agents from chemically armed SCUD missiles, expected in retaliation for the air assault by the Coalition forces. The EOC also asked ARAC to assess the transport and dispersal of radioactive material that might be released by U.S. air attacks on known Iraqi nuclear facilities. This was followed by simultaneous requests from the EOC and from the U.N.'s Evaluation and Planning Program to assess certain effects of smoke plumes from oil wells that might be ignited by the Iraqis as defensive or retaliatory actions.

ARAC personnel were on duty 14 hr a day during much of the 45-day Desert Storm period. The total effort expended by the ARAC staff on analyzing and forecasting the transport and dispersion of smoke plumes caused by the oil fires in Kuwait—180 continuous days—is the most extensive in ARAC's history. Numerous U.S. government agencies, the United Nations World Meteorological Organization, and nine Mideast nations were daily recipients of these calculations. Figure [illegible] shows the operations staff working with some of the products prepared by ARAC during and after Desert Storm.

Meeting the Challenges

Our first challenge was to evaluate the hypothetical dispersal of chemical warfare agents from chemically armed SCUD missiles. This required defining burst altitudes and a credible droplet-size distribution, applying these characteristics to modeling an explosively developed cloud of droplets, and then using the diverse meteorologies of five cities scattered throughout the Mideast to calculate resulting scenarios.

Our approach when this request was received from the EOC was typical of nearly all ARAC responses; that is, we built on and adapted the resources we had and developed new capabilities "on the fly." At first, modifying the computer models and preparing assessments for each city took us a few hours; with experience, plus new and revised computer programs, we soon reduced the process to less than one hour per city. After nearly three weeks of twice-per-night forecasts for Tel Aviv, Jerusalem, Haifa, Dhahran, and Riyadh, the threat of chemical warfare abated, and this capability was held in reserve.

The second request from the EOC—for ARAC to model the dispersal of radioactive material from bombed Iraqi reactor facilities—was easier to respond to because ARAC had been designed to address similar events. The single (but major) problem was acquiring representative meteorological data and transforming it into forms readily usable by our models. All normal weather data transmission from the region (e.g., Iraq, Kuwait, Syria, Saudi Arabia, and Israel) had ceased because of the hostilities. Thus, at first, the only available data consisted of individual profiles of atmospheric variables (e.g., wind and temperature) that we were able to obtain from the U.S. Air Force Global Weather Central (AFGWC). Although extremely valuable, these profiles were not in an immediately usable form. We were forced into an intensely manual mode of operation until codes were developed to decode, reformat, and interpolate these individual profiles for our models. Within a few days, however, AFGWC began providing products from their newly implemented regional meteorological model and supplying gridded analyses and forecasts of most of the essential variables. This regional model was a key to our successful meteorological support during and after Desert Storm.

The effort invested in developing the meteorological data sources and interfaces for the EOC's first two requests paid dividends when the possibility of large-scale oil fires arose later during the war. Detailed terrain data for the entire region, with a horizontal resolution of 100 m, had been acquired shortly before Desert Storm from the Defense Mapping Agency; this input became essential for the regional-scale calculations that were to follow. Our first calculation of the consequences of oil fires was triggered when the EOC asked us to use our three-dimensional models to simulate three burn scenarios originally evaluated by Sandia National Laboratories, Albuquerque, for a study of how oil-fire smoke might be used as a defensive screen for Iraqi troops in Kuwait (Church et al., 1991). Within a few days, we used the meteorological data from our new sources to complete the initial evaluations of the consequences of fires in oil refineries, storage depots, oil wells, and oil-filled trenches, either singly or in combination. By melding an existing model of the thermal rise associated with a fire plume with newly developed algorithms for optical depth (an estimator of sunlight blockage) and horizontal visibility, we were able to prepare realistic evaluations of both hypothetical and real oil-fire scenarios in near real time and to develop forecasts of consequences out to 36 hr in the future (the limit of AFGWC's forecast model). Figure 2 typifies these early consequence assessments that were based on scenarios defined in the Sandia National Laboratories study.

Even as ARAC was developing these oil-fire assessment tools, LLNL's Evaluation and Planning Program asked us to help evaluate the effects of smoke obscuration on various electro-optical "smart" weapons guidance systems for a variety of scenarios and in specific portions of the visible and infrared spectra. We completed several assessments; however, the war ended before we had developed a detailed infrared capability.

During the last two weeks of Desert Storm, ARAC's new capability to provide operational forecasts of the obscuration resulting from oil fires was described in

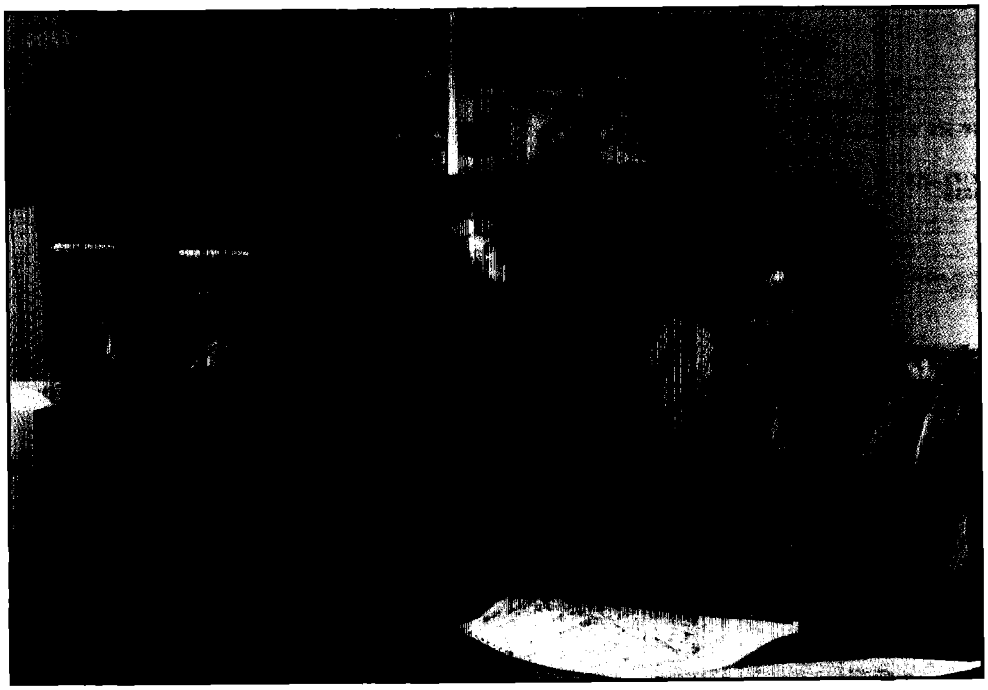


Figure 1. Assessment tools and products used by the ARAC center during the Desert Storm crisis, proceeding clockwise from the foreground: weather-forecast charts, 36-hr forecast of soot dispersion, 36-hr forecast of particle flow over a terrain model. The screen in the background displays an image of a burning oil well.

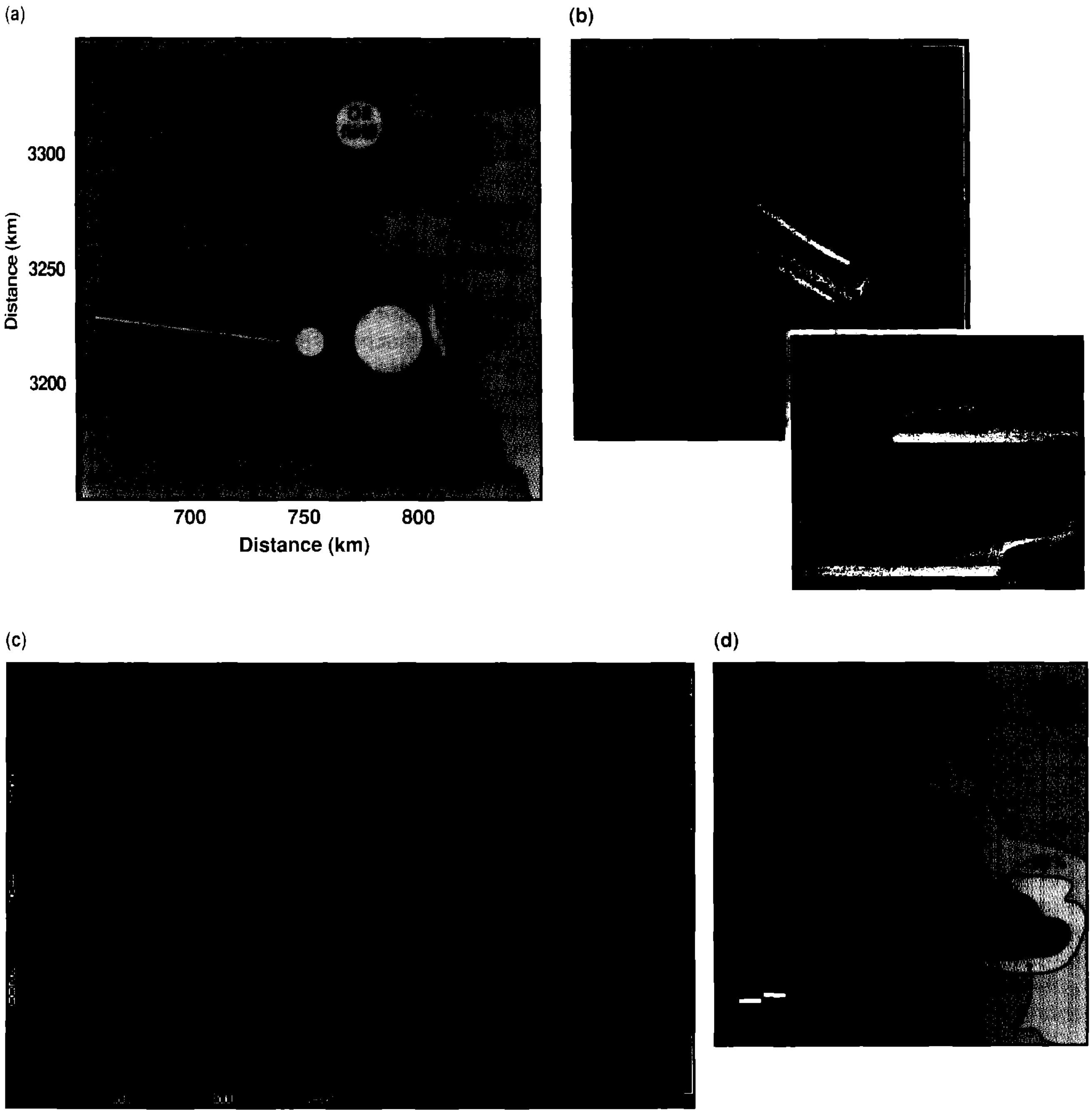


Figure 2 For a scenario provided by Sandia-Albuquerque, we assumed **(a)** that three oil fields, an area including three refineries/storage depots, and a trench filled with oil, had been set ablaze. The trench (actually, a series of 80 approximately 1-km-long trenches) was assumed to be 80 km long, ~3.5 m wide, and 4.5 m deep. Several predictions and data-visualization techniques are shown for different meteorological conditions: **(b)** complex particle dispersion 36 hr after ignition; **(c)** optical depth through the smoke pall 36 hr after ignition; and **(d)** the percentage of 0.55-μm-wavelength light (representing visible light) transmitted to the ground through a smoke pall 48 hr after ignition for a well-fire scenario with winds from the northwest.

briefings to the Pentagon, Central Command and to General Norman Schwarzkopf's staff. ARAC was placed on alert throughout the ground war in case such forecasts were required, particularly in light of the fact that Iraq had ignited the oil field wells. Fortunately, the ground invasion was so swift and successful that the oil fires had no major effect on the battle.

Post-Desert Storm Calculations

When Desert Storm ended on February 28, 1991, all requirements and support for the modeling work being performed by ARAC also ended. However, during March and April 1991, as the world learned of the enormous destruction of the oil fields and the bleak outlook for extinguishing the fires, scientific attention began to focus on possible consequences of the spreading smoke plume (Figure 3). Concerns ranged from fears of global cooling that would lead to a "nuclear winter" to worry about dire consequences to the health of the citizens and the ecology of the region.

The "Desert Storm-induced nuclear winter" issue—that is, widespread climate cooling resulting from smoke and soot blocking sunlight—had first arisen in early January 1991. At that time, scientists had disagreed on whether as many as three to four million barrels of oil burning each day would cause a widespread climate change. There were two reasons why it was not likely that major climatic effects would occur: first, the rate of injection of soot was projected to be only a few percent of that predicted to be capable of inducing a nuclear-winter effect; and second, because the fires were not likely to be hot enough to cause the smoke to rise into the upper troposphere or stratosphere, the smoke would likely be scavenged relatively rapidly by clouds and precipitation and would be ultimately

Figure 3. Typical forecast of the plume structure and location (inset) prepared by ARAC for the U.S. research flights that measured the spreading smoke from the oil fires in Kuwait. The accuracy of the ARAC model is confirmed by the photograph, which was taken by satellite at the approximate time of the forecast. (Also see the comparison shown on the back cover of this report.)

washed out. In parallel with the ARAC developments during Desert Storm, members of G-Division's Atmospheric Microphysics and Chemistry Group completed a global chemistry model calculation of the possible global concentration of the soot and sulfate injected into the atmosphere by the fires. The results from this model showed that concentrations of soot and sulfate would be substantially elevated over background levels throughout a large area surrounding the Gulf region. However, these initial simulations did not support suggestions of a pollutant buildup large enough to induce widespread climate changes.

By late March 1991, a British research aircraft had made the first detailed scientific measurements of the smoke plume. These observations, in concert with numerous aircraft reports, generally corroborated the early model results regarding the rise of the smoke and thus alleviated the fear of cooling on a large scale. However, reports from the Mauna Loa Climate Observatory and the University of Wyoming did reveal some apparent very-long-range transport of smoke particles and the potential for interactions between soot and clouds.

In April 1991, ARAC was again asked to activate its unique modeling capabilities. Two working groups, one sponsored by the World Meteorological Organization (WMO) in conjunction with the World Health Organization (WHO), and the other consisting of members of the U.S. government's scientific community, proposed airborne sampling programs to evaluate and assess the environmental consequences of the oil-well fires. At a WMO/WHO meeting held in late April, the aircraft measurements working group asked ARAC to forecast plume location and structure in support of all aspects of the research aircraft missions, especially in filing flight clearances with air traffic control authorities the evening before each mission. The DOE's Office of Health and Environmental Research (OHER) funded ARAC's support of the U.S. flight program. ARAC began the calculations on May 7, 1991; on May 12, 1991, we began faxing our forecasts to the flight operations base in Bahrain (Figure 4).

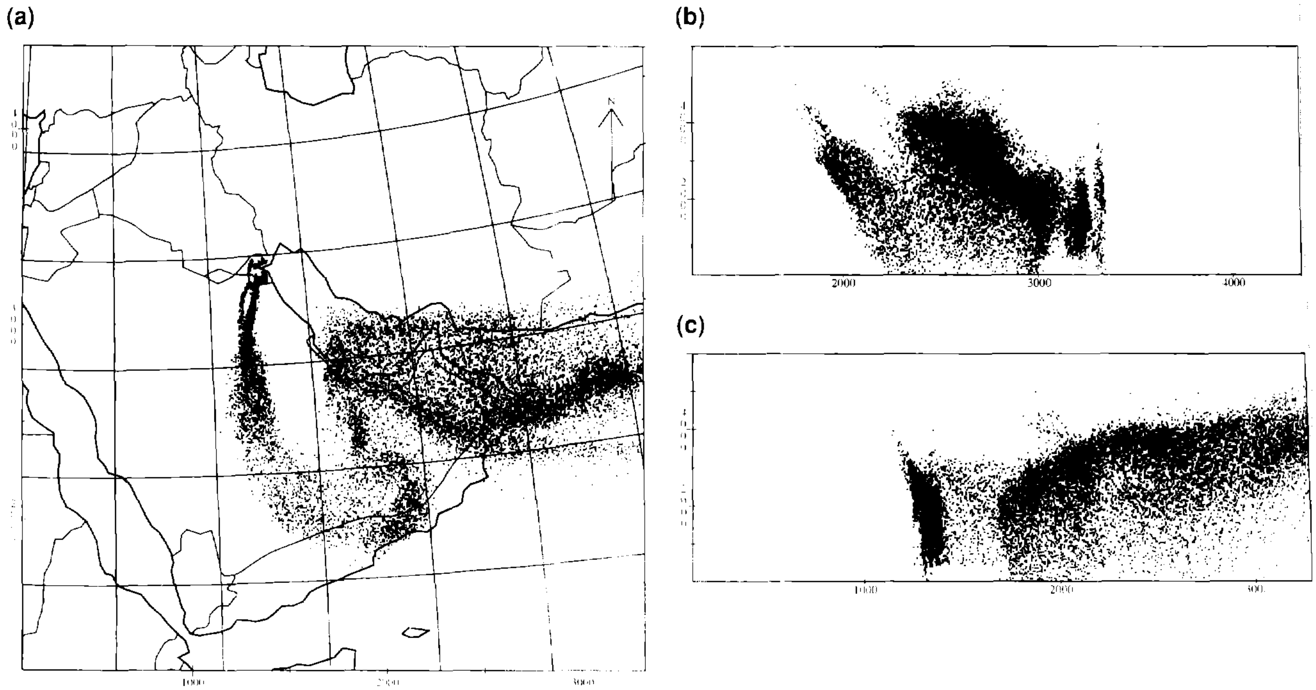
The research aircraft measurement program mounted by the U.S. atmospheric scientific community was conducted in two, four-week-long stages that began in early May and mid-July, respectively. Shortly after the flights began, all the agencies involved, including the National Science Foundation, the DOD, the DOE, the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the National Center for Atmospheric Research, and Battelle Pacific Northwest Laboratory (PNL), began requesting copies of ARAC's calculations and forecasts. These requests were followed by requests from WMO Headquarters in Geneva and from institutions and supporting contractors in the Mideast (e.g., King Fahd University and ARAMCO in Dhahran, Saudi Arabia) and in Washington, DC (e.g., the Defense Nuclear Agency and Pacific Sierra Research).

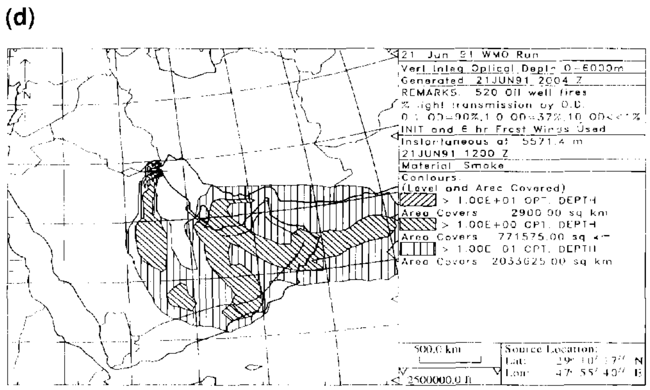
When the first phase of the U.S. research flight program ended in early June 1991, it was thought that ARAC might be able to suspend the modeling effort until the start of the second phase in mid-July. However, many agencies wanted to receive this information for as long as the fires continued to burn. For example, in a specific request to DOE Headquarters, the WMO asked for the ARAC calculations to be continued until the fires were extinguished and also requested ARAC to fax its daily calculations to the meteorological and environmental services of many of the region's governments. The WMO was anxious to generate and maintain interest in ARAC's calculations so that the local governments would be encouraged to continue acquiring a variety of meteorological and air-pollutant measurements; these would be useful in future evaluations of the effect of the oil-fire plumes on the region. Thus, by early June, ARAC was also faxing its calculations to Iran, Kuwait, Pakistan, Oman, Bahrain, Qatar, Yemen, Turkey, and Saudi Arabia. By this time, 20 agencies and countries were receiving daily ARAC calculations.

The relative accuracy of ARAC's modeling in comparison to satellite images is shown in Figures 3 and 4. In particular, Figure 4a–d shows two ways of displaying the dispersal of the smoke plumes; Figure 4e, a satellite image taken 4 hr before the time of the ARAC predictions, reveals close agreement with the main segments of the plume over central Saudi Arabia and weak to unknown agreement with the older, more dispersed eastern segment of the plume. For this series of calculations, we used a 3200-km domain and a vertical resolution of 15 levels in 6 km.

In July, we modified our codes at PNL's request to generate plots showing areas of the plume that were of specific ages (e.g., 12, 24, 36 hr removed from their generation at the oil fire). With this information (Figure 5), the DOE/PNL research aircraft could acquire samples for characterizing the chemistry of the aging soot particles. Until the sampling program ended on August 16, 1991, we provided intensive calculational support for all aspects of its planning and execution.

On our own initiative, we began calculating the long-range transport of the dispersing soot particles from the oil fires in Kuwait. For these calculations, we used a Northern Hemisphere version of ARAC's transport and diffusion models. Although coarse in horizontal resolution (381 km), we retained the same vertical resolution as the regional calculations and





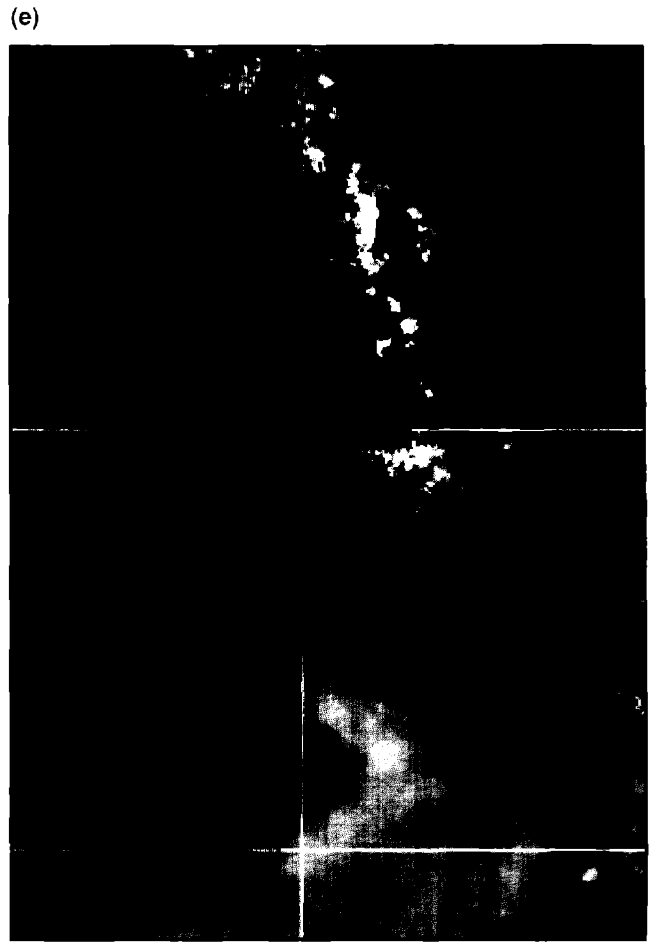


Figure 4. Forecasts prepared by ARAC after the conclusion of Operation Desert Storm: **(a)** overhead view of a typical set of calculations on a 3200-km grid of 6 km depth in which the structures of the plumes are depicted with marker particles from the ADPIC model, **(b)** east-to-west view, **(c)** south-to-north view, and **(d)** isopleths (contours) of optical depth indicating the relative sunlight blockage caused by the presence of the plumes. For comparison, **(e)** shows the large regional extent of the plumes as detected by the visible-wavelength scanner aboard a U.S. Air Force Defense Meteorological Satellite Program satellite. The satellite picture was taken 4 hr before the time of the ARAC prediction.

also retained the terrain structure. Our results show the very persistent northwesterly to southeasterly flow *out of the Gulf* region, followed by complex transport and mixing patterns as the diluted plume interacts with the seasonal monsoonal flow over Ethiopia, Somalia, the Arabian Sea, India, Southern Asia, and eastward (Figure 6).

Samples taken during the research flights showed that the particles were mostly hygroscopic; that is, they would probably leave the atmosphere as they became condensation nuclei for clouds and raindrops. Therefore, although we do not believe that many of the soot particles would be transported as far as depicted in our model, the calculations do indicate the potential long-range effects of these fires. We anticipate that data from stations participating in the WMO's Global Background Air Pollutants Monitoring (GBAPM) program will provide a source of verification.

We observed several events that suggest a correlation between precipitation anomalies and the presence of soot from the oil fires; these include a large negative monsoon-season precipitation anomaly in Pakistan and northwestern India and a positive precipitation anomaly on India's southwestern coast. The historic Bangladesh cyclone in late April 1991 and severe floods in China during late May and the first week of July 1991 also appear more than coincidentally correlated with the dispersion of soot particles as indicated by our long-range calculations. Further research may be able to help determine the significance of these apparent correlations.

ARAC completed its calculations for the oil-well fires on November 1, 1991, a few days before the last fire was extinguished. All meteorological data for both the 3200-km and northern hemisphere grids have been archived for possible future research studies. We have also archived all contour plots created and transmitted since the onset of Desert Storm. Follow-on work should include:

- Studying the soot-particle-precipitation anomalies.
- Verifying our transport calculations using the GBAPM data and satellite imagery.
- Publishing a catalog of daily plume positions as generated by the ARAC models and as visible in photographs taken by weather satellites.

Mount Pinatubo Response

While we were in the midst of responding to the situation in the Gulf region, Mt. Pinatubo in the Philippines erupted on June 12–22, 1991. The AFGWC requested ARAC's assistance in creating volcanic ash cloud aviation advisories for the region of the Philippine Islands. The advisories were to aid in the evacuation of U.S. military

Figure 5 Plot showing areas in which the smoke plume is a given number of hours removed from its source. By using this information when samples were collected, it was possible to analyze how the particles in the plume changed with age.

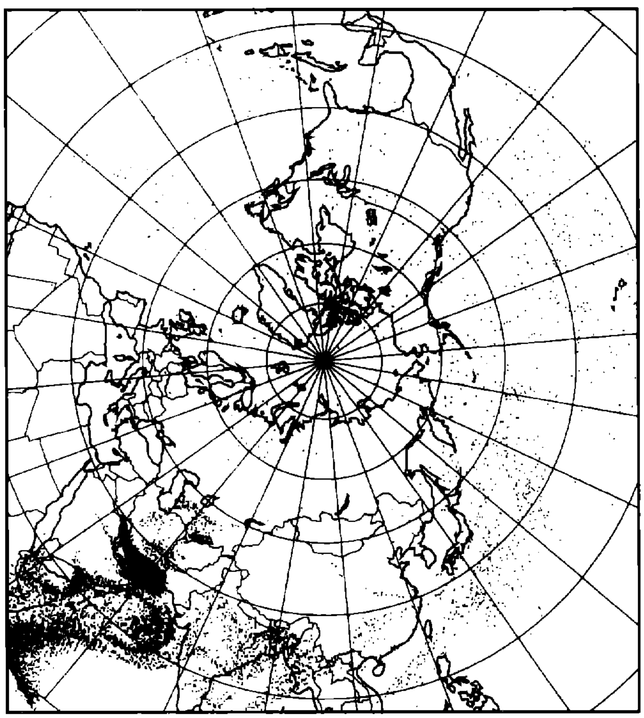


Figure 6 Particle dispersal calculated on April 1, 1991, for 1524 hr of continuous release from the oil fires in Kuwait. Although this calculation did not allow for particle removal by condensation, it was clear that soot particles could become widely dispersed.

and dependent personnel from the region. Except for an internal experimental attempt to model one of the eruptions of Mt. Redoubt, Alaska (December 1989), ARAC had no prior experience in modeling volcanic eruption ash hazards. Through application of our three-dimensional material transport and diffusion models using AFGWC meteorological analysis and forecast wind fields, we were able to provide the U.S. Air Force with ash-cloud-position advisories extending to 48 hr in 12-hr increments for a period of five days during the evacuation flights. The advisories consisted of "relative" ash cloud concentrations in ten layers (surface to 5000 ft, 5000–10,000 ft, and every 10,000 ft up to 90,000 ft). The ash was represented as a log-normal distribution of solid particles ranging from 10–200 µm in diameter. We simulated ash-cloud dispersion and size-dependent "ashfall" over time as the eruption clouds dispersed. These products were sent to the AFGWC (Offutt Air Force Base, Nebraska) and Headquarters, First Weather Wing (Hickam Air Force Base, Hawaii) via fax for further distribution to U.S. Air Force weather units throughout the Pacific region.

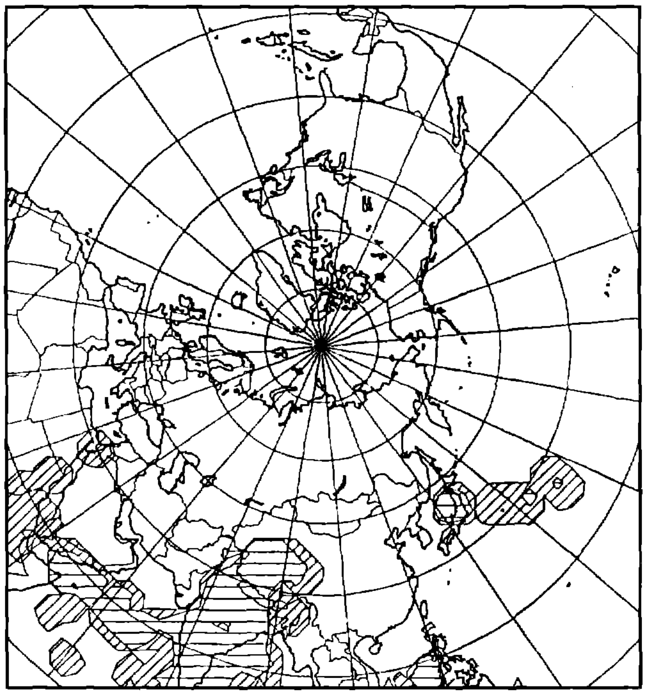


Figure 7. An example of one of the first Mt. Pinatubo ash-cloud advisory maps prepared for the U.S. Air Force on a hemispheric scale. This plot was for the 20,000–30,000 ft layer valid at 0000 GMT, June 20, 1991. The ash levels are relative to the initial release.

Model Data Requirements

To satisfy the request for ash-cloud advisory forecasts, we required physical information about the eruptions (source terms to the model) such as location, times/duration, height, and width/diameter of the release, and the size/density of the ash. The U.S. Air Force provided most of this event-related information. The assumptions on ash particle size distribution were based on scientific studies of the El Chichón and Mount St Helens eruptions.

Initially, ARAC's "hemispheric" models (developed in response to the Chernobyl accident) were used, because twice daily Northern Hemisphere wind field analyses are routinely received and archived. With AFGWC priority assistance, ARAC began receiving forecast wind data for 15 standard pressure levels of the atmosphere. By the conclusion of the first response day, ARAC had produced the first set of ash-cloud advisory products, as shown in Figure 7, using the hemispheric scale model discussed previously. Unfortunately, the meteorological and dispersion model domain boundary was close to the eruption site. This meant that these calculations were of limited utility to the south and southwest of Mt. Pinatubo. They did, however, cover the primary evacuation route from Cebu to Guam, which remained ash free.

Shortly after transmission of the first calculations, the U.S. Air Force requested comparable advisories for a more detailed subregion of a few thousand kilometer extent centered on the Philippines. Figure 8 delineates this model's subdomain and also reveals the complex, sheared wind flow regimes at 2500 and 15,000 m on June 18, 1991. To prepare these subregion calculations, ARAC personnel had to extract grid-point profiles from the hemispheric data grids and merge them with available regional rawinsonde data. At the time of the eruptions, this was a manual process; now it is substantially automated.

Using the same "source" scaling parameters and preceding eruptions, Figure 9 reveals the model representation of the June 19, 1991, 1425 UTC eruption after 9 hr of dispersal simulation. Note the dominant plume of ash transported west-southwest over the South China Sea by the strong high-altitude winds. A low-altitude, meandering plume (from residual venting between major eruptions) stretches north around Taiwan and wraps back around along the south China coast. Vertical cross-section views of this June 19, 1991, eruption plume at 0000 UTC on June 20 show the simulated "ashfall" from the southwestward transported upper plume (5–15,000 m) and the smaller low-level plume. The resulting dispersing ash clouds are shown in Figure 10a–c, revealing the different structures of the northeast (lower level) ash stem and

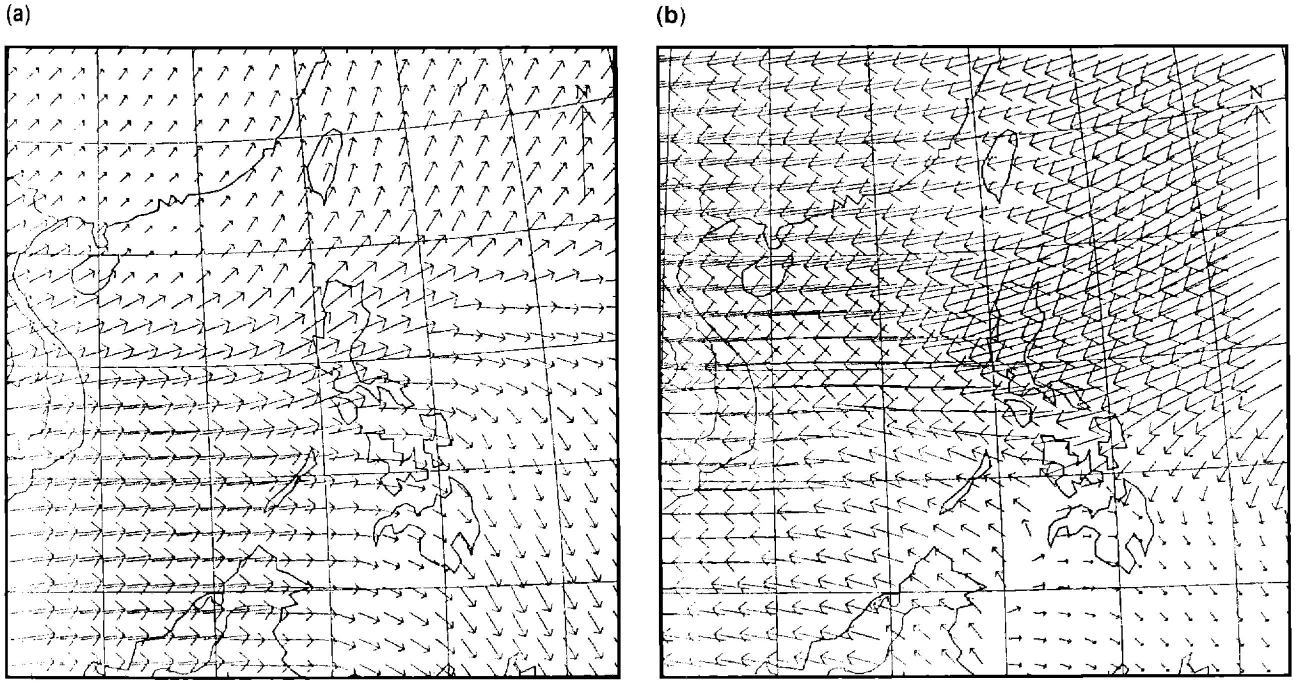


Figure 8. Details of the regional calculations for the June 19, 1991, Mt. Pinatubo eruption: **(a)** lower atmosphere winds (~7500 ft), and **(b)** upper atmosphere winds (~50,000 ft).

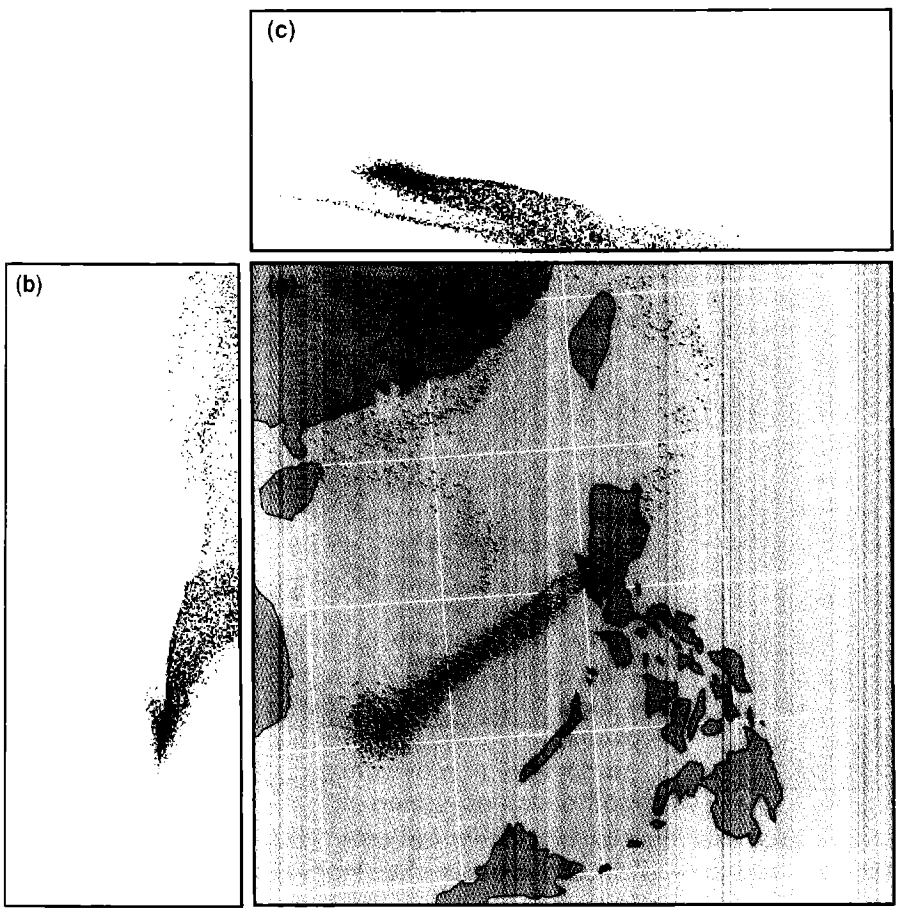


Figure 9. The regional grid calculations of the June 19, 1991, Mt. Pinatubo eruption: **(a)** overhead particle cloud view, **(b)** east-to-west view, and **(c)** south-to-north view.

vent clouds and the southwest (upper level) main explosion cloud and ashfall from the stratospheric injection. Figure 10d is an AFGWC analysis that verifies ARAC's calculations. Immediately evident is the sloped, upper cloud and particle fallout structure being driven to the southwest by the higher altitude winds while the lowe "stem" and the ash clouds resulting from continuou lower-altitude venting are being swept first to the north east, then northward. Note the need for a much broade cloud near the source point in the ARAC calculations.

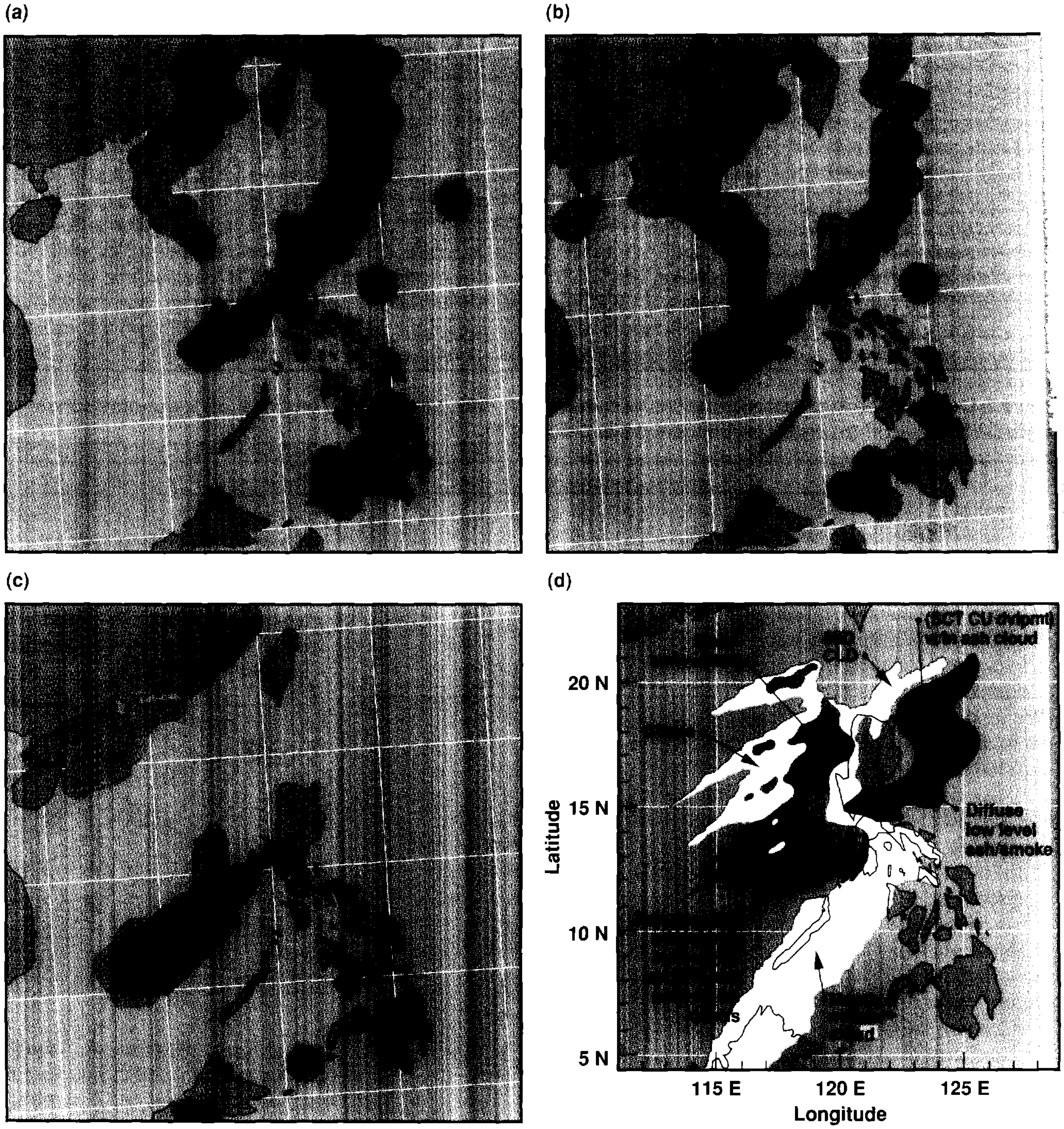


Figure 10. The relative ash concentration isopleths for three altitude layers: (a) 5000–10,000 ft, (b) 10,000–20,000 ft, and (c) 20,000–30,000 ft. (d) An AFGWC real-time satellite cloud and ash analysis that verifies ARAC's prediction.

For the cataclysmic eruption of June 15–16, 1991, the complex three-dimensional atmospheric structure in the region produced dramatically divergent ash cloud patterns. The large eruptions (>7–10 km) produced ash plume clouds with strong westward transport over the South China Sea, Southeast Asia, the Bay of Bengal, toward India, and beyond. It is the downwind transport, diffusion and ash fallout of these enormous stratospheric intrusions that resulted in the numerous aircraft encounters with the ash clouds, leading to engine damage. The low-level eruptions (<7 km) and quasi-steady-state venting produced a plume that generally dispersed to the north and east throughout the support period.

Lake Shasta Toxic Spill Response

On the night of July 14, 1991, a railroad tank car derailed and spilled about 19,000 gallons of metam sodium herbicide into California's Upper Sacramento River approximately 3 miles north of Dunsmuir, California. This river flows directly into the northernmost finger of California's largest reservoir and popular recreation area, Lake Shasta. By the afternoon of Monday, July 15 (the day after the spill), the herbicide had traveled about halfway along its 45-mile trip to Lake Shasta (Figure 11). As it moved down the deep canyon leading to the lake, the water-soluble metam sodium decomposed into hydrogen sulfide and methylamine gases. Residents along the river were advised to evacuate the area, and a 50-mile stretch of Interstate 5 was temporarily closed. The slick was expected to arrive at the upper reaches of the lake by Tuesday morning, July 16. The multiagency response group was concerned that the still waters of the lake and the enlarged surface area of the elongated slick would contribute to an increased rate of evaporation in the strong summer sunlight (photodissociation) and that this might create a large cloud of toxic gases. The question of whether or not to evacuate residents and vacationers along the Sacramento River arm of Lake Shasta led California's Office of Emergency Services (OES) to ask ARAC to use its dispersion modeling capabilities to determine the maximum credible air concentrations that could be expected from the evaporation of this herbicide (Baskett et al., 1992).

The OES first obtained approval to use ARAC through the DOE San Francisco Office on the afternoon of July 15, and then provided ARAC with a source term estimate by 1700 PDT. We were asked to estimate the maximum instantaneous and 8-hr average air concentrations for the pool evaporation from 0600 to 1100 PDT on Tuesday, July 16. We responded in about 90 min, and, within that time, all pertinent chemical input data were collected, terrain data were extracted, a model grid was built, the dispersion model MATHEW/ADPIC was run, and plots were delivered to OES.

Dispersion Conditions

ARAC estimated that the atmospheric stability would be neutral all day. Figure 12 shows instantaneous cross-section and overhead views of the particle locations at 1000 PDT (about 4 hr after the

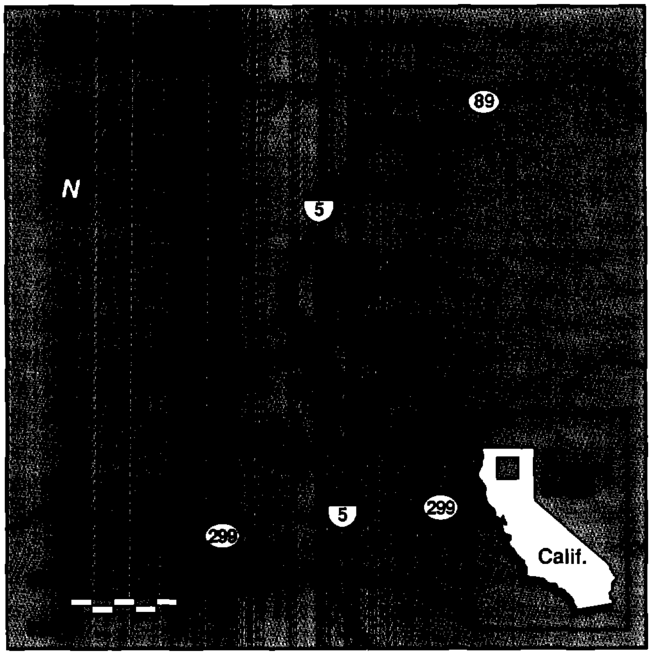


Figure 11. Map of the Upper Sacramento River and Lake Shasta region affected by the metam sodium spill.

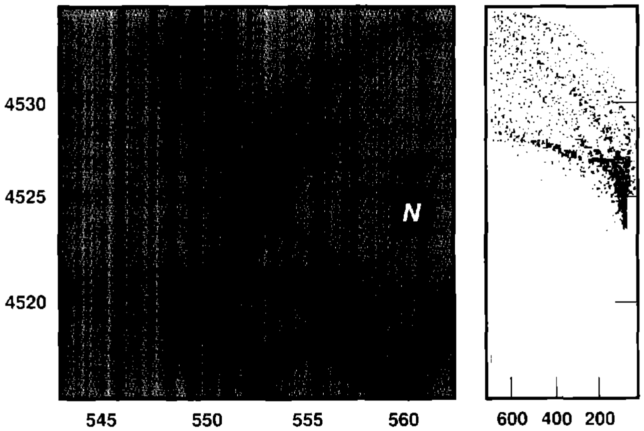


Figure 12. Instantaneous cross-section and overhead views of particle locations 4 hr after the release began. (Also see the cover illustration of this report.)

release was assumed to begin). The figure also indicates how the gas would likely spread across the tip of the lake and move up the western facing slopes of the ridge north of the lake. After 5 km of travel, the gas cloud was predicted to extend to 600 m above ground. This excellent upslope flow dispersion would rapidly dilute the cloud.

Contour Plots

Contour plots were produced for instantaneous and 8-hr average methylamine and hydrogen sulfide (H_2S) air concentrations. The maximum modeled values were compared with the American Conference of Governmental Industrial Hygienists threshold limit values in Table 2. With its higher emission rate, the H_2S became the primary concern. Comparing instantaneous concentrations with a 15-min average short-term exposure limit adds considerable conservatism.

Figure 13 is a sample contour plot for the 8-hr H_2S integrated air concentration. The instantaneous H_2S and methylamine plots showed a similar pattern with contours extending northeastward. The maximum values were all located on Lake Shasta. Based on these calculations, an evacuation of the area was not considered necessary.

Southern Pacific officials began aerating the metam sodium pool early Sunday morning, July 21. The maximum air concentration measured within the water curtain surrounding the aerator was 4 to 5 ppm. Although this concentration was measured over an aerated lake surface, it compared favorably with the model's maximum instantaneous concentration of 9 ppm by quiescent evaporation.

ARAC System Upgrades and Modernization

Technological changes, including new generations of computers, communications systems, and graphics terminals, have permitted continuous system improvement in performance speed, reliability, and graphics presentation over the last decade. Likewise, the application of software development tools and methodologies have improved ARAC's software reliability and management.

In 1989, we began a major project to develop a new UNIX-based, modern workstation for the computers at sites directly supported by ARAC. Completing this work will provide faster modem communications, high-quality color graphics, the MOTIF graphical user interface, and laser printer quality output to all of these facilities. Future enhancements will deliver sophisticated models and databases to each site's emergency response and assessment staff.

To assure its readiness to respond effectively, ARAC constantly tests its entire system by conducting an active exercise program. Releases of inert substances that trace atmospheric motions and other opportunistic events are used to evaluate and validate the entire system. ARAC's experience in the many exercises and alerts and during actual radiological and nonradiological events have resulted in emergency dispersion capabilities that now range from local-to-hemispheric scales. Each new type of event has given us the opportunity to identify areas in which ARAC's emergency response service could be improved and expanded. As a consequence, much of ARAC's growth has resulted from "lessons learned" being transformed into new capabilities (Sullivan, 1988, 1989).

One of our most recent additions to ARAC is an automated meteorological data-request and management system that can acquire raw data immediately and can decode or process these data within 2 min, for anywhere in the world. Today, our models are set up so that they can be expanded from their generally local focus up to near-continental scale within a few hours.

The current ARAC service can:

• Rapidly assess environmental impacts, using three-dimensional, diagnostic, atmospheric-dispersion models that include the effects of complex meteorological conditions and terrain.

• Support emergency-preparedness plans and activities at over 50 DOE and DOD facilities within the U.S. These sites are accessible through the ARAC computer system.

Table 2. Modeled concentrations compared with threshold limit values for the Lake Shasta release.

	Methylamine (ppm)	H_2S (ppm)
Short-term exposure limit	—	15
Maximum instantaneous modeled concentration	2.4	9
Time-weighted average	10	10
Maximum 8-hr modeled concentration	0.12	0.6

• Provide timely impact assessments to DOE authorities for accidents that occur anywhere in the world.

ARAC is now well-prepared to respond to accidents involving radionuclide releases that can have consequences and/or be measured at long distances from the accident site. Likewise, it can also address the regional and long-range assessment of toxic material dispersion in cases such as the oil fires in Kuwait and the volcanic ash transport and fallout from the eruption of Mt. Pinatubo. The enhanced graphical display tools and products available to the ARAC operations staff (with highlights of our plume modeling in the complex terrain of Europe) were featured in the January–February 1990 issue of *Energy and Technology Review* (LLNL, 1990). Our improved regional modeling for the Kuwaiti oil fires was featured in the December 1991 of *Energy and Technology Review* (LLNL, 1991) and in recent reports (Ellis et al., 1992).

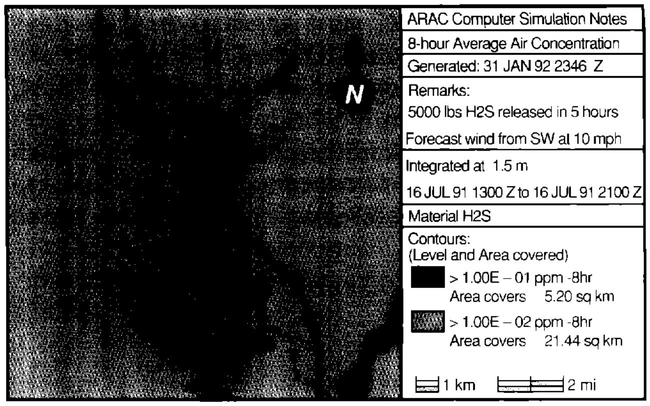


Figure [illegible]. Contour plot of an 8-hr H_2S integrated air concentration on July 16, 1991. These calculations indicated that an evacuation of the Lake Shasta area was not necessary.

Future Expansion

DOE has indicated that it desires an expanded ARAC program to provide state-of-the-art emergency response assessments on a worldwide basis. Beginning in 1993, we expect to start construction of a new, permanent building to house a much expanded ARAC staff and their equipment. In 1994, we plan to begin the implementation of prognostic meteorological models to support critical "lead time" emergency decisions.

Within two years, we expect six more DOE facilities to be added to the ARAC system. We also plan to include toxic chemicals as part of ARAC's emergency response service if we can find appropriate DOE or other federal agency sponsorship. Initially, this will require modeling a selection of nonreactive, buoyant, and heavier-than-air toxic gases. The early focus of this effort will likely be associated with chemicals stored and used at DOD and DOE facilities. If and when the Environmental Protection Agency decides to certify codes for episodic (i.e., emergency) releases, ARAC would submit its codes for certification.

Our next systems' improvement will encompass replacing the current DEC PRO 350/380 site systems with UNIX/ULTRIX high-performance workstations that incorporate the MOTIF user interface ("windows") standard and the technology of the present ARAC mainframe models.

Advanced dispersion models are currently in the research and development phase. We plan to incorporate more complete physics into these models to address explosively generated thermal cloud rise and stabilization in the ambient atmosphere, radionuclide transformation to daughter products (nuclides), and integration of accident field measurements in a source term "predictor-corrector" adjustment technique.

ARAC plans to support the development of a local-to-regional (meso) scale meteorological forecast model in order to provide predictive winds, stability, and turbulent diffusion values for creating hazardous material advisories. These are required for evacuation planning/activation in major accidents. Currently, ARAC is limited to a short term (1–3 hr) "persistence" projection (of conditions), which is far too restrictive when large numbers of people are at risk and detailed planning is required. Recent advances in atmospheric modeling, numerical solution techniques, and computer power should now make mesoscale prognostic modeling an achievable goal by 1995–96.

We also need to be able to represent the discrete spatial rainout/washout of hazardous materials, such as occurred over various parts of Europe, Scandinavia, and Russia during the Chernobyl accident. New data sources (e.g., NEXRAD radar systems with gridded radar precipitation estimates) and a new mesoscale "wet" prognostic model, should be able to provide the data and/or forecasts of precipitation with the discrete space and time resolution necessary to advise authorities of the rapid development of hazardous "hot spots" resulting from washout deposition.

Summary

Once again during 1990–91, ARAC has been challenged to support a complex and unique set of emergencies brought on by war, nature, and transportation.

In 1991, the ARAC staff spent over 225 days on "emergency" status. DOE has determined it will support the expansion and modernization of ARAC so that it can be a truly worldwide capability, prepared to assess any radiological accident in which the U.S. has interests or concerns. Thus, we expect to see, in the next several years, major growth in the ARAC program.

Group Members

The work described in this article was performed by, or under the auspices of, the Atmospheric Release Advisory Capability Group. Scientists involved include Thomas J. Sullivan (Program Director), Rosemary O. Abriam, Ronald L. Baskett, Diane F. Bonner, Edward Bush, D. Carol Chapman, Keith T. Chiles, Wanda Chiu, Stephen P. Cooper, J. Daryl Crew, Charlayne L. Deming, James S. Ellis, K. Patrick Ellis, Kathleen M. Fischer, Connee S. Foster, Kevin T. Foster, Robert P. Freis, Donald A. Garka, Yolanda G. Glaeser, Anthony T. Hoang, Bryan S. Lawver, Denise A. Leddon, John S. Nasstrom, Brenda M. Pobanz, Leon Richardson, Kristie A. Sasser, Walter W. Schalk, III, Mark E. Spruiell, Denise A. Sumikawa, Khai Trinh, Charles Veith, Phil Vogt, Hoyt Walker, and Jon G. Welch.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Assistant Secretary for Defense Programs; the Department of Energy, Assistant Secretary for Nuclear Energy, Naval Reactors; the Department of Energy, Assistant Secretary for Environmental Restoration and Waste Management; the Department of Defense, Defense Nuclear Agency; the Department of Defense, U.S. Navy; the Department of Defense, U.S. Army; EG&G, Mound Applied Technologies, Inc.; Sandia National Laboratories, Livermore; General Dynamics Corporation, Electric Boat Division; and the United Kingdom, Ministry of Defence.

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Numerical Modeling of Complex Dispersion Phenomena

Donald L. Ermak, Group Leader

The Atmospheric Flow and Dispersion Modeling Group models flow and dispersion, including releases of heavier-than-air gases, over spatial domains ranging from the local scale, in which buildings are important, to the mesoscale, in which topography plays a significant role.

Our group develops, evaluates, and applies numerical fluid dynamics models in local to mesoscale studies in which the topographic conditions, physical properties of the released material, or both have a significant impact on the atmospheric dispersion of the emission. Topography can affect the spread of an emission in several ways. Important effects can result from surface roughness and obstacles to the flow, which at the mesoscale are mountains and valleys, while at the local scale, they are structures such as buildings. The heating or cooling of the atmosphere and ground surface can also alter the flow pattern.

The most important physical property of the released material is its density, especially for gases that are heavier than air. Density affects the buoyancy of the resultant vapor cloud and its dispersion in the atmosphere. The dispersion of a nontoxic dense-gas release is generally a local problem because the concentration levels of concern are usually high and the area of the hazardous region is limited. However, the situation is different for a *toxic* dense-gas release because interest in cloud dispersion may extend out into the mesoscale region, where dense-gas effects of the released gas can be neglected.

Our main efforts are directed toward developing and applying more accurate wind-flow and dispersion modeling capabilities. These modeling tools allow us to study the physical processes that govern atmospheric transport and dispersion, and can also be used to generate realistic predictions of expected concentration levels in cases of accidental release. Our interests in the field of atmospheric flow and dispersion are broad. We are concerned with combustible, toxic, and radioactive releases ranging in size from trace amounts, in which dispersion is determined by the ambient atmospheric conditions, to large releases, where in-cloud properties such as density, initial velocity, and turbulence level dominate the flow and dispersion of the released material. The dispersion domain is equally broad, extending from the local scale, where buildings and other structures can be important, to the mesoscale, where topography plays a significant role.

We use several models to treat these phenomena in computer simulations. These models vary in the completeness of their description of the important physical phenomena, and, correspondingly, in numerical complexity and the computer memory and speed required to conduct simulations. The models are generally developed to treat a class of release scenarios. For example, the treatment of dense-gas releases requires the inclusion of several physical processes that can be ignored in trace-gas releases. Similarly, much greater computational speed is needed in an operational emergency-response application than in planning or research applications.

This article presents some of the highlights in modeling atmospheric flow and dispersion. These include:

- Use of our building-wake modeling capability for assessing air quality around building complexes.
- Application of our mesoscale conservation-equation model to drainage flows within mountain valleys.
- Application of our mesoscale modeling experience to regional climate studies.
- Development and use of our dense-gas conservation-equation model to assess the effectiveness of vapor barriers in mitigating the consequences of large liquefied natural gas (LNG) releases.
- Development of a variable-terrain dense-gas version of the Lagrangian particle advection-diffusion (ADPIC) dispersion model.

Local to Mesoscale Atmospheric Flows

Our earliest and current operational approach to the problem of simulating atmospheric dispersion over complex terrain uses the two-model system called

MATHEW/ADPIC (Sherman, 1978; Lange, 1978). MATHEW (*mass adjust the wind*) generates three-dimensional, mass-consistent wind fields using a limited number of wind observations. These wind fields are input to ADPIC, a Lagrangian particle advection-diffusion model that simulates the dispersion of a trace release by calculating the trajectories of marker particles. This two-model system employs two of the basic conservation principles: conservation of mass (MATHEW) and conservation of species (ADPIC). Together, they are considered to be a diagnostic model in the sense that simulations are based on observed winds, and, consequently, predictions of future wind-field conditions are made by assuming persistence of the observed wind field.

To obtain a true forecast capability, we are developing prognostic models that are based upon the full set of conservation equations, namely, conservation of mass, momentum, energy, and species. In this regard, we are pursuing two modeling approaches: a more precise nonhydrostatic model called FEM-PBL [Finite-Element Model for the Planetary Boundary Layer (Leone and Lee, 1989)], and a simpler hydrostatic model called SABLE [Simulator of the Atmospheric Boundary Layer Environment (Zhong et al., 1991)]. The hydrostatic equations are derived from the nonhydrostatic equations by assuming that the pressure can be determined solely from the temperature and density and is therefore independent of the velocity. This approximation is valid for situations in which the vertical motions are relatively weak—for example, in the atmosphere over rolling hills or in coastal regions. Because it takes considerably less computer time to solve the hydrostatic equations than the nonhydrostatic set, it is cost-effective to use SABLE rather than FEM-PBL whenever appropriate.

The method used to solve the conservation equations is an efficient blend of finite-element and finite-difference techniques. The isoparametric finite-element method is used to divide the solution domain into a large number of irregularly shaped, nonoverlapping subregions (finite elements) that may be of unequal sizes. Each element has four (vertical) sides and a top and bottom that are not necessarily horizontal. The solution of the problem is then approximated on each of these elements in such a way that the parameters of the representation become the unknowns. The geometric flexibility of this method not only allows us to accurately represent terrain, but also permits us to concentrate grid resolution where it is most needed to generate accurate and cost-effective solutions. For example, smaller elements are employed only in regions in which a fluid property such as velocity, temperature, density, or concentration changes rapidly within a short distance. In this way, we do not waste a large number of small elements where they are not needed.

We are also developing a new and evolving finite-element code for transient, nonhydrostatic, incompressible flow called TIVFS (Transient Incompressible Viscous Flow Simulator). In contrast to FEM-PBL, TIVFS permits arbitrary (unstructured) meshes, is semi-implicit in time (no diffusional-stability limit on the size of the time-step), and utilizes the "consistent mass matrix" that is inherent in the finite-element method. The consistent mass matrix approach generates more accurate solutions of the pure transport (advection) process, especially on the coarse meshes usually used in our simulations because of practical limitations. Thus far, this code can only be used for the "pure" Navier-Stokes equations. However, the conversion to a planetary boundary layer (PBL) code by the inclusion of an appropriate turbulence model and other necessary modifications is expected to be straightforward.

The conservation-equation models are valid for local problems involving the flow around buildings as well as mesoscale problems in which the flow is over hills or along valleys. When the dimensions of the emission source can be resolved by the numerical grid, the conservation-equation models can also calculate cloud dispersion (as well as the wind field) because the models include the species equation. However, in many applications the source dimensions and the size of the dispersing cloud cannot be affordably resolved by the numerical grid. In this case, we use the FEM conservation-equation models to generate wind fields and input these results into the ADPIC Lagrangian particle dispersion code to determine the dispersion of the released material.

Air Quality Around Building Complexes

One of the major challenges of the building-wakes project is to accurately model atmospheric flows around buildings. The flow pattern around an arbitrarily shaped building is complicated, and extremely fine resolution is required to model the flow field. For purposes of testing our models and building an expertise in this class of problems, we have chosen to first simulate the flow and dispersion over structures that are represented by simple, isolated, rectangular blocks. Even these relatively simple structures produce turbulent flow patterns filled with unsteady motions, which are relatively difficult to calculate.

To address these problems, we are using two different but complementary approaches. To achieve the near-term goal of providing a usable model for assessment purposes, we extended our Reynolds-averaged

FEM-PBL conservation-equation model by adding the k-e formulation to represent turbulence (Lee, 1992). Although this standard approach has been widely and successfully used in a variety of engineering and atmospheric applications, there are a few limitations that must be considered. For example, the temporal-averaging procedure, which forms the basis for the Reynolds-average approach, precludes detailed information concerning instantaneous peak-to-peak values of the time-varying fields (e.g., concentrations), which may be one of the important determining factors regarding health effects.

Our second approach to modeling turbulence attempts to address the instantaneous-value issue by using the large-eddy simulation (LES) technique. This approach directly simulates the resolved large eddies, while remaining subgrid-scale processes are parameterized. Although this approach is expected to be computationally expensive and unsuitable for routine use in assessment calculations, we plan to exercise the model for special situations in which important physics needs to be understood or when fine details of the turbulence structure must be simulated. We also plan to use the model for bench mark studies and as a test-bed for developing improved turbulence models for the computationally simpler Reynolds-averaged formulation.

As an example of a practical application of our k-e turbulence model, consider the buildings shown within the computational domain in Figure 1. The finite-element mesh is graded such that the finest resolutions are located next to the solid boundaries. A steady wind that increases as it approaches the buildings from the left is imposed. The free-stream Reynolds number based on the 40-m-high building is about 2.8×10^7, and the atmosphere is neutrally stable.

To calculate the dispersion from a point source, we interpolate the FEM velocity field onto an equally spaced ADPIC mesh, with the buildings represented as terrain. The interpolated ADPIC velocity fields for the cross-sectional planes at $z = 10$ m and $y = 194$ m are shown in Figure 1. For demonstration purposes, a calculation is performed with a point source placed at position B. The plume associated with this source is represented by a continuous release of particles throughout the period of integration. As a first approximation, the turbulent diffusivities used in the ADPIC part of the calculation are derived from formulas that involve the horizontal (σ_h) and vertical (σ_z) standard deviations of the plume dimensions, with values based on the Pasquill-Gifford curves. In the future, we plan to use turbulent diffusivities that are calculated in the FEM model using the k-e formulation.

The projections of the velocity vectors onto the cross-sectional planes at $y = 194$ m (Figure 1a) and $z = 10$ m (Figure 1b) depict the main features of the flow, which consist of separation and recirculation zones above and aft of the dual structures. The flow behind the taller building is channeled toward the left by the shorter, but wider, building downstream. An unsymmetrical, left-tilting, building wake is generated behind the taller building. We note that the recirculation zones behind each building are characterized by relatively low velocities. This observation suggests that pollutants released within these inactive regions will not be appreciably dispersed by advective processes.

Figure 2 shows the evolution of the calculated particle-dispersion patterns after the release is initiated. At early times, the particles tend to aggregate within an area close to the source because velocities within the recirculation cavity between the buildings are relatively low. Most of the particles are transported across the downwind face of the building and are entrained into the separated region around the corner along the

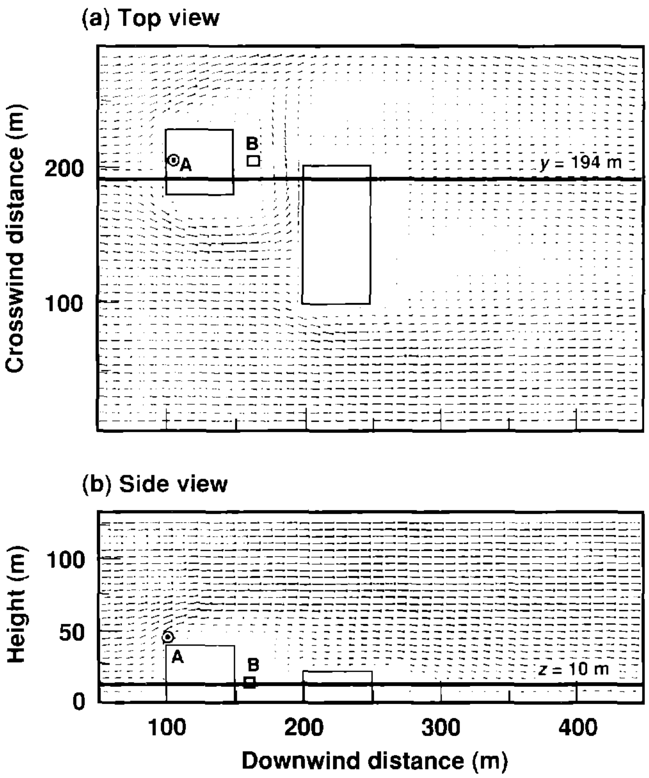


Figure 1. The model-generated velocity field around two buildings. **(a)** Top view at a height (z) of 10 m, and **(b)** side view at a crosswind distance (y) of 194 m. **A** and **B** are locations of point sources.

adjacent face of the 40-m building. Some of the particles diffuse into the mean flow and are carried downstream. The dispersion pattern shown at 2.0 min (Figure 2c) suggests that the particles have now migrated up from ground level along the downstream face of the building and have merged into the separation zone around the corner of the building. The plume now becomes widely dispersed, but high concentration levels are maintained within the region in the neighborhood of the source.

Modeling Drainage Flows in Mountain Valleys

The U.S. Department of Energy–sponsored Atmospheric Studies in Complex Terrain (ASCOT) program is designed to increase knowledge and understanding of terrain-dominated flows, with specific emphasis on nocturnal flows within mountain valleys. One of the ASCOT-sponsored field studies involved the Mesa Creek Basin in western Colorado. The purpose of the study was to investigate the seasonal frequency of occurrence of drainage flows along the sloped surfaces and within the basin, and to evaluate the effects of the ambient meteorology on their development. We have been using our nonhydrostatic FEM-PBL conservation-equation model to study the development of these flows.

The Mesa Creek Basin, situated on the north slope of Grand Mesa, encompasses an area of roughly 10 × 20 km located about 30 km east of Grand Junction, Colorado. The topographic features of the Mesa Creek drainage basin resolved within the modeled terrain are shown in Figure 3. The study area is bounded on the south and west sides by Grand Mesa, by a ridge on the east side, and by Plateau Valley toward the north. The terrain varies in height from 3200 m on Grand Mesa to about 1500 m within the basin. The slope-generated flows drain into the basin, where

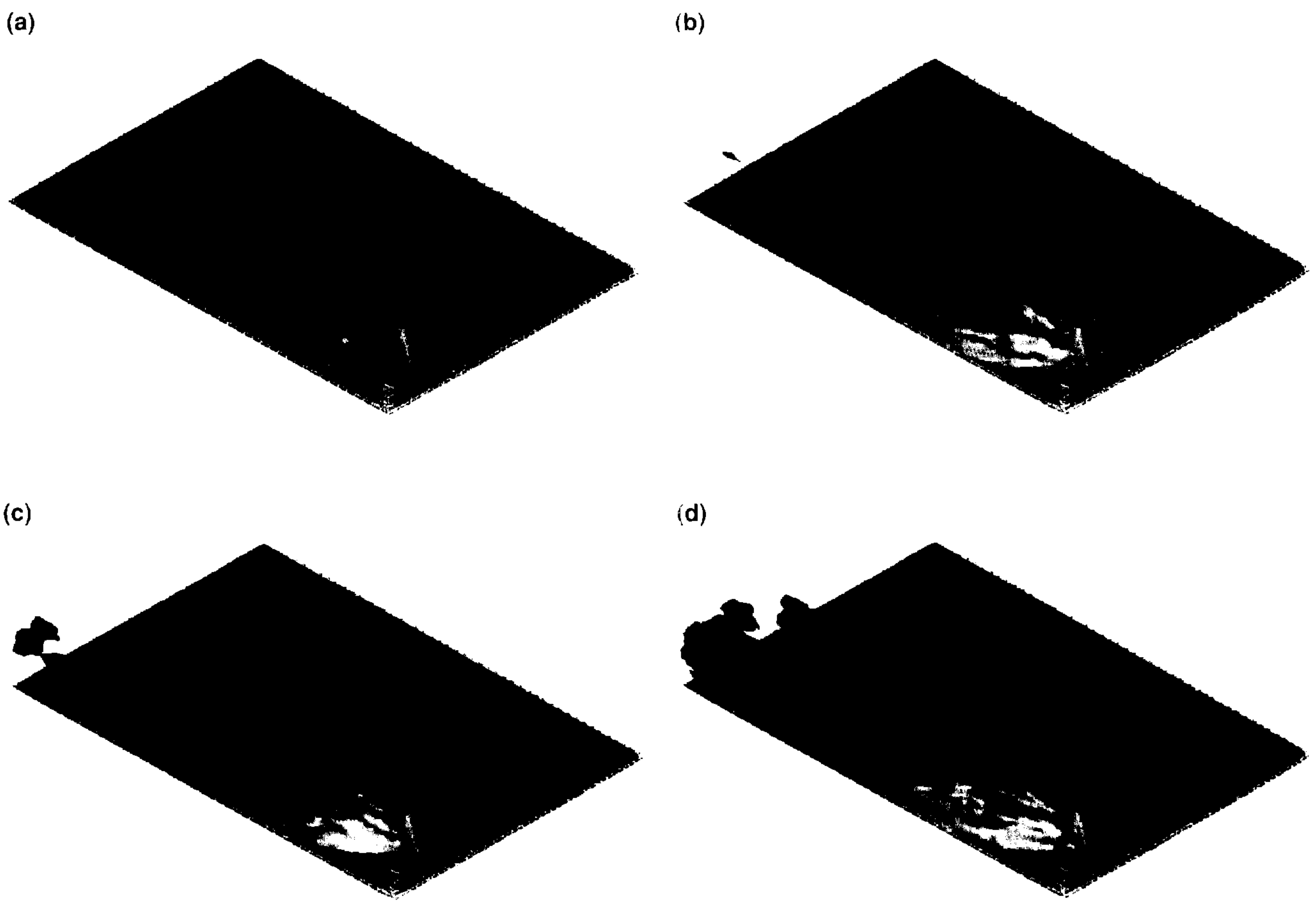


Figure 2. Calculated cloud-dispersion pattern for a tracer release located at source **B** (see Figure 1) between the two buildings. Figures (a) through (d) respectively show the dispersion pattern at 0.5, 1.5, 2.0, and 3.0 min after the continuous release is initiated.

they merge with those generated within Plateau Valley, whose drainage area is largely situated east of the study area. The flows within Plateau Valley subsequently drain westward into the Colorado River drainage area.

The simulation reported here (Leone and Gudiksen, 1991) is for a simple undisturbed nocturnal flow development. The large-scale geostrophic wind and the initial velocity field are assumed to be zero. The initial potential-temperature field is taken to be slightly stable, with a vertical gradient of 1 $K \cdot km^{-1}$ and horizontal uniformity. The driving force is a surface heat flux of 40 $W \cdot m^{-2}$ applied uniformly on the domain for a period of 2 hr. Figure 4 illustrates the development of the drainage flow at 7.5 m above the ground as the cooling proceeds for 2 hr. Three distinct drainage regions can be seen: one originating on the southeast rim of the basin, a second coming from the center of the mesa, and the third flowing off the west wall of the basin. These merge into a single down-basin flow through the center of the basin.

Regional Climate Modeling

In conjunction with the University of California, Davis (UC Davis), we are conducting a mesoscale climate modeling study under the sponsorship of the National Institute for Global Environmental Change (NIGEC). The purpose of this study is to investigate the impact of CO_2-induced greenhouse warming on the regional climate. At present, most of the effort is concentrated on developing the procedure for nesting the UC Davis fine-resolution regional model (Jang, 1990) into the relatively coarse resolution of the climate data. As part of this effort, we are improving the model parameterizations of the physical processes such as atmospheric radiative transfer, the cloud microphysics, the treatment of the soil and vegetation surface layer, and the surface fluxes of heat and moisture. We also plan to nest the mesoscale model into an appropriate general circulation model for climate change studies. When completed, the model will be a tool for regional climate studies as well as for short-term local weather forecasting.

The initial and lateral boundary conditions for our initial simulation of mesoscale flow are derived from the twice-daily operational analysis for February 17, 1986, provided by the National Meteorological Center (NMC). The model domain covers much of the western United States (California, western Nevada, and southern Oregon). The model employs fine vertical resolution near the ground surface and in the upper troposphere.

The model topography (Figure 5a) is characterized by two major mountain ranges, the Coastal Range and the Sierra Nevada, with a narrow stretch of the Central Valley running approximately parallel to these ranges. The large-scale flow is from the west to the southwest, and it has a relatively large moisture content.

For this large-scale flow, the topography gives rise to a distinct pattern of mountain-induced precipitation (Figure 5b). Heaviest precipitation occurs on the upslope of the Sierra Nevada. Secondary precipitation maxima that are also associated with topographic upslope flow appear along the northern California coast. Precipitation in the Central Valley and along the eastern side of the Sierra Nevada is relatively light and is due to residual condensate advected by the wind.

The simulated precipitation pattern also suggests the importance of explicit treatment of the microphysical processes for better simulation of precipitation. A similar calculation (not shown) in which only a cumulus parameterization is used (without explicit treatment of the microphysical processes) yielded only narrow bands of precipitation at the topographic upslope rather than the relatively wide areas of precipitation as predicted when microphysical processes are explicitly represented.

Dispersion of Dense-Gas Releases

Over the past decade, we have developed two dense-gas dispersion models: FEM3A (Chan, 1988) and SLAB (Ermak, 1990a). Both models include mathematical

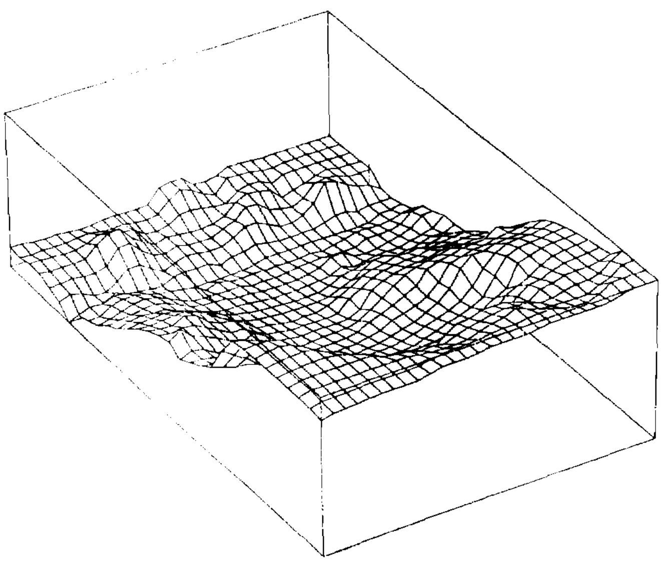


Figure 3. Perspective view of the Mesa Creek region looking north from Grand Mesa toward the Plateau Valley. The area shown covers about 14 km from east to west and 22.5 km from north to south.

descriptions of dense-gas dispersion physics including gravity spread, turbulence damping due to stable density stratification, and ground heating effects. FEM3A provides the more detailed and complete description of the physics of dense-gas flows because it solves the full set of conservation equations in three dimensions, while SLAB employs simplifying assumptions regarding the cloud shape in order to reduce the conservation equations to only one dimension.

Because it is fully three-dimensional, FEM3A can treat flows over varying terrain and around structures, and it can represent the complex structures of the released clouds, including (1) the self-induced vortices that are typical of dense-gas flows, (2) cloud bifurcation that has been observed during dense-gas releases under stable, low-wind-speed conditions, and (3) cloud deflection caused by sloping terrain.

Recently, we also added a *k-e* turbulence parameterization to FEM3A and are conducting an assessment of its performance. The *k-e* turbulence submodel is expected to greatly expand our original local-equilibrium K-theory (eddy diffusivity) treatment to include the creation, transport, and destruction of turbulence. This level of turbulence model is essential for complex flows involving structures such as a vapor fence, barrier, or building.

In SLAB, terrain is assumed to be flat, and the conservation equations are spatially averaged to reduce the numerical description to only one dimension, namely downwind distance. Using assumed profiles for the cloud shape, we can treat the cloud as either a steady-state plume, a transient puff, or a combination of the two depending on the duration of the release. The main advantages of the SLAB code are its low computing requirements, its short running time, and its capability for simulating a variety of sources including a ground-level evaporating pool, an elevated horizontal jet, a stack or elevated vertical jet, and an instantaneous volume source.

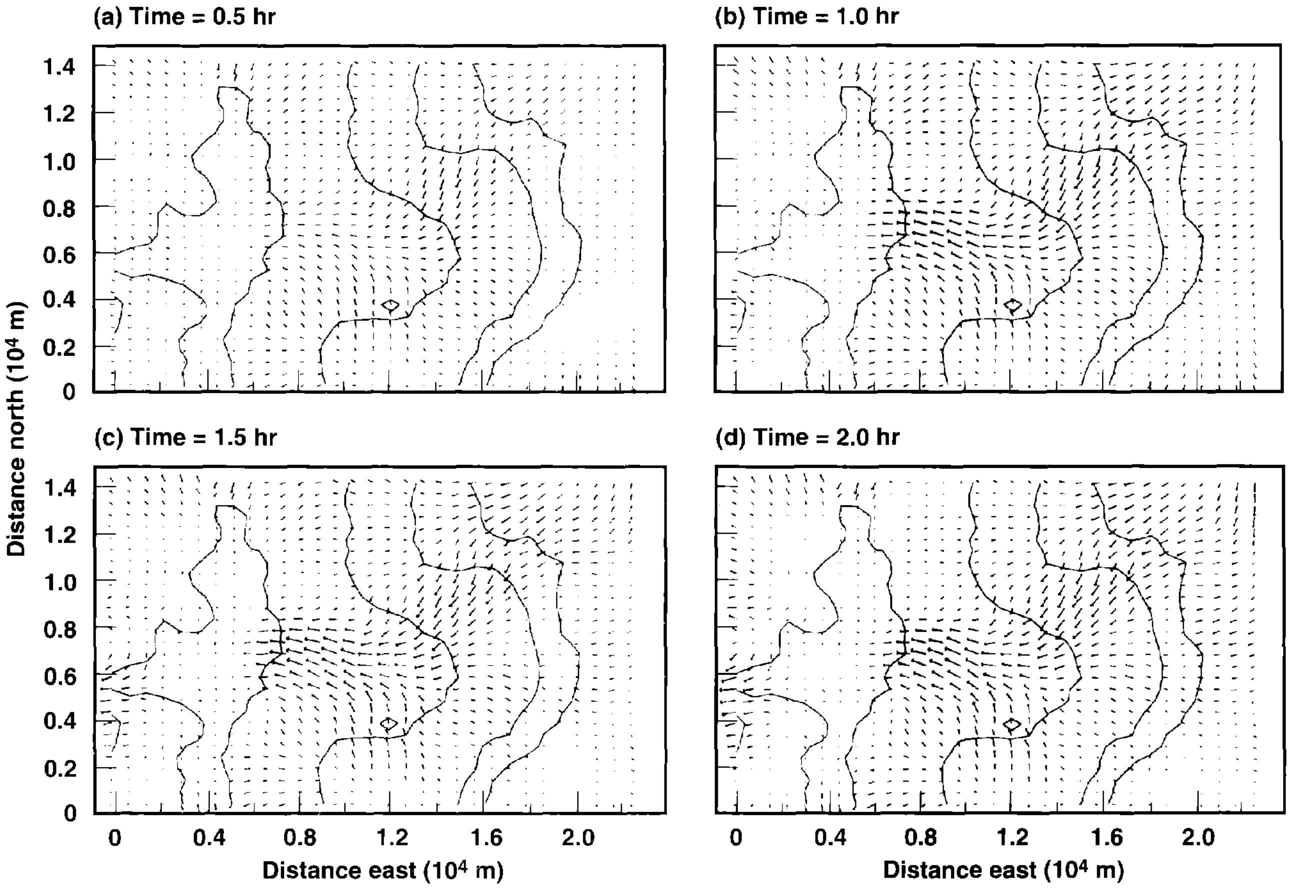


Figure 4. Growth of drainage flow in the Mesa Creek region. The horizontal velocity vectors at 7.5 m above ground level are plotted over the terrain contours for each 0.5 hr of the simulation. The arrows point in the direction the wind is blowing, and the arrows' lengths are proportional to wind speed.

The SLAB model was designed to treat both the near-source, dense-gas region and the far-field, neutral-density region; however, it does not include variable terrain and spatially varying winds. To treat the complications of terrain and varying wind fields without having to use a complete three-dimensional conservation model such as FEM3A, we are modifying our ADPIC advection-diffusion dispersion model, using SLAB model concepts, so that it includes the main effects of dense-gas dispersion.

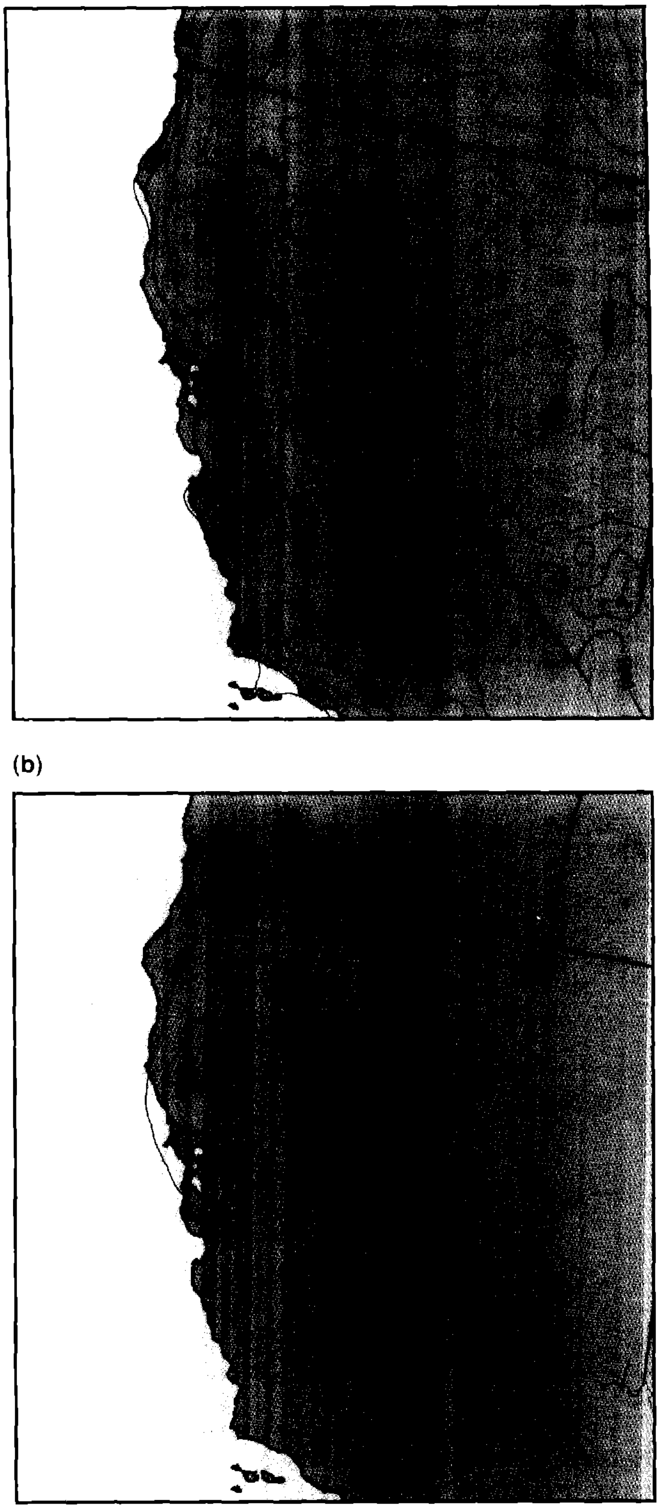
Modeling High-Density Releases in FEM3A

In our FEM3A conservation-equation model, a generalized anelastic approximation formulation of the conservation equations was employed to permit density changes ($\Delta\rho/\rho_a$, where $\Delta\rho$ is the density change from cloud to air, and ρ_a is the density of air) beyond the Boussinesq limit, and also to preclude sound waves. Over the years, the model has accurately simulated a wide range of laboratory and field-scale experiments in which the density of the released gas was less than a factor of about 1.6 times that of air. In addition, the model was observed to conserve species mass reasonably well (typically within a few percent) even though mass conservation is not rigorously ensured by the anelastic formulation. However, recent applications have revealed that the lack of conservation of species mass and global mass (air plus emitted species) is quite significant when the density of the released gas relative to air is much greater than a factor of 2.0 (e.g., chlorine or hydrogen cyanide).

To expand the range in density change for which FEM3A is suitable, we developed two new conservation options (Chan and Gresho, 1992). The first option rigorously conserves species mass and is suitable for problems in which the global mass is not known or is inconvenient to determine, such as cases with open boundaries. The second option rigorously conserves both species mass and global mass and is suitable for problems in which the global mass is known and remains constant. In both cases, the new algorithms require virtually the same computer time as the old algorithm.

As an illustration of the effectiveness of the new procedures in FEM3A, consider the results for a problem in which a ground-level source of heavy-gas material is instantaneously released and dispersed in a rectilinear enclosure. The released material is assumed to have a molecular weight ten times that of air, and the initial distribution of the material is Gaussian about a well localized source on the ground surface. The atmosphere was assumed to be initially isothermal. A mesh graded away from the source was used. In addition, constant diffusivities (with different values in the vertical and horizontal directions) were assumed in the simulations.

(a)



(b)

Figure 5 (a) Topography of the model domain (1060 × 1340 km). Contour-line values are in meters. (b) Accumulated precipitation (cm) for the first 8 hr of the model simulation. High (H) and low (L) points of precipitation are indicated.

We solved the problem in three ways: using the original algorithm, the species-conserving scheme, and the scheme conserving both species mass and global mass. Figure 6 compares the time variations of the total inventory of species mass and global mass using the original and species-conserving schemes. These results show that, at the end of the simulation, the original scheme has lost about 30% in species mass; this loss of mass is also apparent in the curve for global mass. On the other hand, the species-conserving scheme was not only able to conserve species mass exactly, but it was also able to conserve global mass reasonably well. The zig-zag behavior of the curves in Figure 6b was indeed completely eliminated when the additional global-mass conservation constraint was imposed.

Figure 7 compares the concentration and velocity projection on a horizontal plane just above the surface obtained using the original algorithm and the scheme conserving both species mass and global mass. Only one-half of the problem domain has been represented because of symmetry across a vertical plane. The results reveal general agreement in the overall velocity field and the size of the vapor cloud. However, significant discrepancies exist in the region of higher

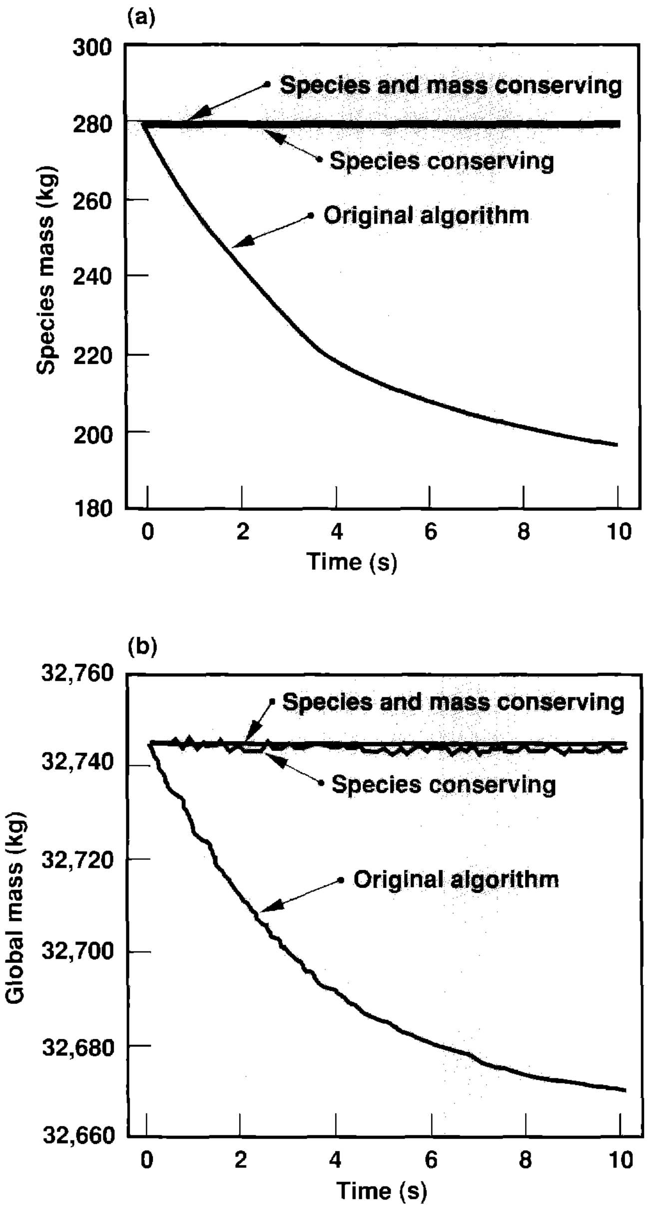


Figure 6. Comparison of mass inventory for **(a)** species mass, and **(b)** global mass, as obtained with the original algorithm that did not conserve mass and with the species-conserving, and species- and mass-conserving algorithms. Note the difference in scales and the non-zero baseline for mass in (a) and (b).

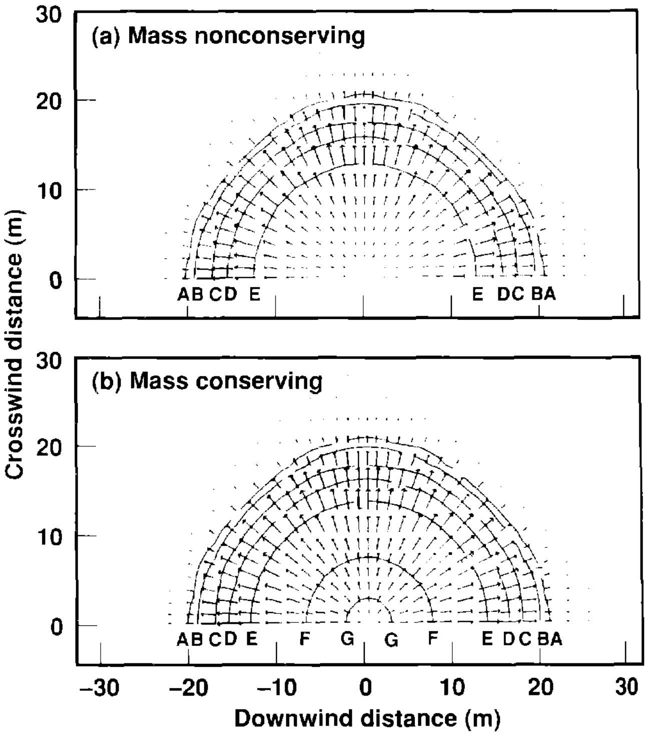


Figure 7. Comparison of predicted concentration and velocity projections on the horizontal plane at a height of 0.5 m at 10 s, with **(a)** mass-nonconserving, and **(b)** species-mass- and global-mass-conserving schemes. The contour levels (in % vol) are: A, 0.1; B, 0.2; C, 0.5; D, 1; E, 2; F, 5; and G, 10.

concentration. The original scheme grossly underpredicts the maximum concentration by a factor of nearly 4. Also, the corresponding flow field is generally less energetic, with its maximum speed reduced by as much as 12%.

Because the additional constraint of global-mass conservation has practically no effect on velocity, concentration, or species mass, the errors associated with the original scheme are identified with the omission of a certain term in the species-conservation equation. The omission of this term turns out to be equivalent to adding a sink term in the species equation in the region of higher density, where most of the species mass is contained. This fact explains why the original scheme suffers a substantial loss in species mass, and in global mass as well.

Modeling a Large Release of LNG

In our mitigation study of the dispersion of LNG vapor from a large release, we applied FEM3A to the simulation of four large-scale LNG vapor-barrier field experiments and conducted a comparison of the results with the relevant field data (Chan, 1992). As shown in Figure 8, the model reproduced the peak concentration of the experiments within a factor of 2. Other predicted results, including cloud arrival time, persistence time, and temperature drop (not shown), are also within a factor of 2 under most circumstances. Our study indicates that an LNG vapor fence can significantly reduce the downwind distance and hazardous area of the flammable vapor clouds. However, a vapor fence could also prolong the cloud persistence time in the source area, thus increasing the potential for ignition and combustion within the vapor fence and the area nearby.

Developing a Dense-Gas ADPIC Model

Several dense-gas atmospheric dispersion models have been developed over the past decade. However, none appears to be suitable to an emergency-response situation requiring simulations over complex terrain and with variable winds. The one-dimensional conservation-equation codes, such as SLAB, are intended for applications over flat terrain and with constant winds, and the three-dimensional conservation-equation codes, such as FEM3A, are not suitable for operational use at this time because they require supercomputers, large amounts of computer time, and a knowledgeable user. Thus, the need exists for a dense-gas dispersion model that is capable of efficient simulations under realistic conditions.

To address this need, we are developing a dense-gas version of the ADPIC Lagrangian particle advection-diffusion model (Ermak, 1990b). Our approach treats the effects of dense-gas dispersion as a perturbation to the ambient flow by modifying the wind field and diffusivity within the dense-gas cloud. The perturbed wind field is calculated from conservation of momentum and energy principles using a vertical averaging approach that was developed in the SLAB dense-gas dispersion model for calculating local thermodynamic properties such as density and temperature. The diffusivity used in the new version of ADPIC is an adaptation of the dense-gas, K-theory diffusivity developed for FEM3A.

The temperature of the release gas often plays an important role in determining the evolution of the density of the dispersing cloud. When the release temperature is low enough, mixing of the released gas with the surrounding air produces a cloud that is denser than air even if the molecular weight of the released gas is less than that of air. In practice, this phenomenon will occur when the released gas is stored at cryogenic temperatures (e.g., LNG) or when it is stored at ambient temperature under pressure (e.g., chlorine and ammonia) and the pressure drop at release results in a rapid expansion and a corresponding drop in temperature. To simulate this important effect, we recently added to the ADPIC code the capability to treat the dispersion of *cold* dense-gas releases.

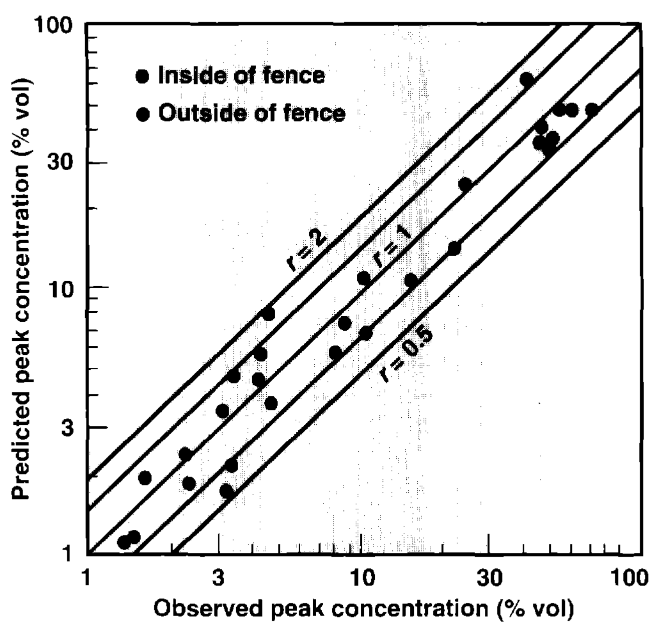


Figure 8 Comparison of predicted and observed maximum peak values of concentration at sample locations inside and outside of the vapor fence. The quantity *r* is the ratio of the predicted value to the observed result

An advection-diffusion model, such as ADPIC, does not include a description of thermal transport that is independent of mass transport. Consequently, when cloud-air mixing is adiabatic, the calculation of the thermodynamic properties of the cloud is fairly straightforward, but it is more complicated when ground heating of the cloud is important. To overcome this limitation, we made use of the Lagrangian particle aspects of the ADPIC model and made two additions to the normal advection-diffusion process. First, we included a "thermal energy deficit" with each marker particle that decreases with time because of local ground heating. Second, we included a thermal expansion term in the marker-particle displacement equation that is proportional to the local rate of ground heating.

Using this approach, the transport of thermal energy in the cloud and the transport of mass of released gas are described in similar yet independent ways. The transport of mass of released gas is determined by using the normal particle-in-cell technique, namely, it is calculated from the trajectories of the individual marker particles and the constant mass associated with each particle. Similarly, the transport of thermal energy is described by the trajectories of the individual marker particles and the time-varying "thermal energy deficit" associated with each particle.

Figure 9 shows ADPIC simulations of atmospheric dispersion for release of an isothermal neutral-density gas (air) and a cold dense gas (chlorine). These simulations illustrate some important features associated with dense-gas dispersion. The atmospheric condition is slightly stable (Pasquill-Gifford class E). The figure shows a top and side view of the clouds 2 min after the continuous releases are initiated. The dense-gas cloud is seen to be considerably wider and lower than the neutral-density cloud. This change in cloud shape is the result of the two major dense-gas dispersion effects. The first is a reduction of turbulent mixing within the vapor cloud due to stable stratification of the dense layer. The second is the generation of gravity-spreading flow due to density gradients in the horizontal direction.

Future Directions

In the near term, we plan to complete (1) model development and evaluation of both our local-scale and dense-gas k-e turbulence parameterizations within our conservation-equation models, and (2) our modifications to the ADPIC model for the treatment of denser-than-air releases. Turbulence is an area of special concern. We are improving the parameterization of

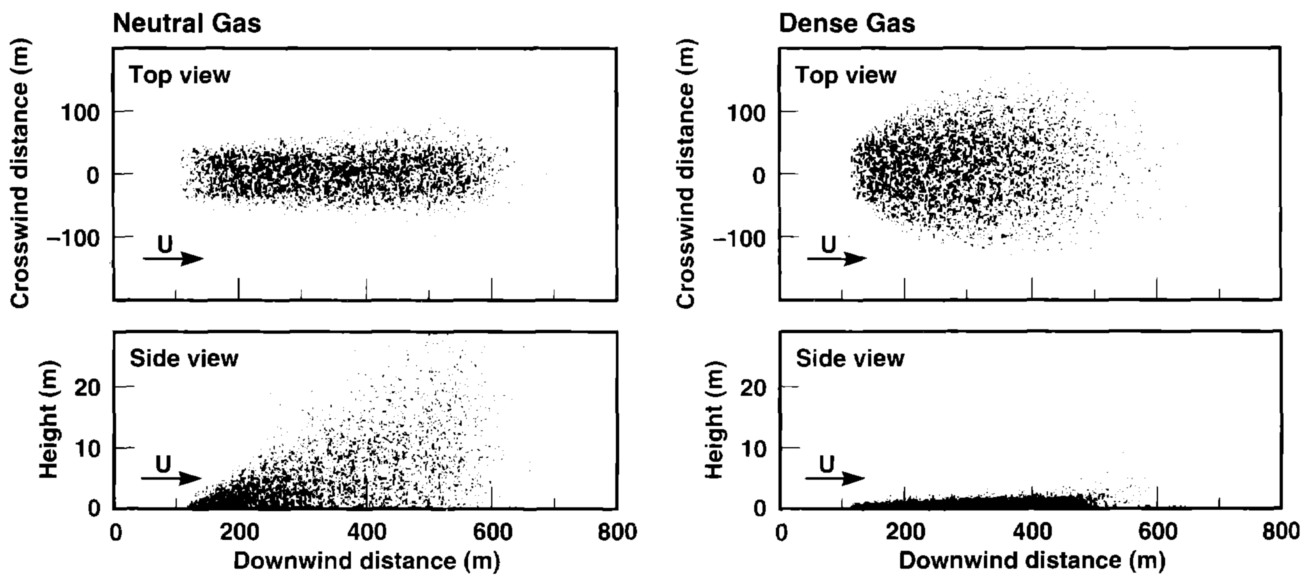


Figure 9. ADPIC model simulation of atmospheric dispersion for a neutral-density gas (air) release and a dense-gas release. The dense-gas cloud is considerably wider and lower than the neutral-density cloud. The arrows indicate the wind (U) direction.

ambient turbulence in the ADPIC code, and for our conservation-equation models, we are planning to develop an atmospheric-transport-equation model (such as a *k-e* model) for dispersion problems in the planetary boundary layer. Other physical processes such as radiation, precipitation, and fog formation are also being considered for inclusion in our models.

In addition to improving the model physics, we will explore new numerical techniques and coding structures to improve the accuracy and efficiency of our codes. Furthermore, the advent of relatively inexpensive yet powerful computer workstations and the use of parallel processors will affect both the development and use of our models for research and operational applications. Current workstations are powerful enough to run many simulations of interest, and they can also provide robust and interactive graphics. These capabilities will greatly improve our ability to display and analyze the modeling results, and thereby aid in understanding the complex physical processes occurring in the atmosphere and their effect on the dispersion of a release under realistic conditions.

As understanding of the various atmospheric dispersion processes increases and our ability to simulate them improves, we plan to transfer these capabilities from the research to the operational arena. Our Atmospheric Release Advisory Capability (ARAC) emergency response system currently relies mainly on the MATHEW/ADPIC suite of codes for making atmospheric transport and dispersion predictions. Applying the results of our past research, we plan to improve both the MATHEW and ADPIC codes and add a prognostic wind-field model, such as SABLE, to the system. Our long-range goal is to achieve operational use of these models, first within the ARAC context, and then within industry through our technology transfer program.

Group Members

The work described in this article was performed by, or under the auspices of, the Atmospheric Flow and Dispersion Modeling Group. Scientists involved include Donald L. Ermak (Group Leader), Stevens T. Chan, Philip M. Gresho, Jinwon Kim, Robert L. Lee, John M. Leone, Jr., Rose C. McCallen, Howard C. Rodean, J. Alan Ross, and David P. Turner.

We are participating with a number of researchers from other laboratories, universities, and institutes whose contributions are not fully reported here. Appendix B provides a brief summary of these interactions.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division; the Department of Defense, U.S. Air Force, Engineering and Services Center; the Department of Defense, U.S. Army, Chemical Research Development and Engineering Center; the Environmental Protection Agency; the National Institute for Global Environmental Change, University of California, Davis; the LLNL Laboratory Directed Research and Development program; and the LLNL Environmental Protection Department.

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Atmospheric Dispersion of Radionuclides and Hazardous Materials

Paul H. Gudiksen, Group Leader

The Model Applications and Nuclear Effects Group develops models that simulate the dispersion of radionuclides and hazardous materials into the atmosphere. We apply these models to real and hypothetical accident scenarios.

The Model Applications and Nuclear Effects Group has developed several models that can accurately simulate the release, atmospheric dispersion, and deposition of radionuclides and hazardous materials. A demonstration of these capabilities was provided by our simulations of the dispersion of the radioactivity injected into the atmosphere as a result of the Chernobyl nuclear reactor accident in the Ukraine; our models accurately estimated the amount of cesium (^{137}Cs) released, its dispersion in the atmosphere, and its subsequent deposition over Europe. Our participation in both national and international research programs includes analyzing data, developing and evaluating models, and coordinating and modeling field experiments conducted in complex terrain.

Over the past decade, we have focused our efforts on developing atmospheric dispersion models to study the fate of emissions on local-to-continental scales. Our models have been applied to real nuclear reactor accidents, such as Three Mile Island, and to hypothetical accident scenarios associated with the storage, maintenance, and transport of nuclear weapons systems. We have also developed nuclear weapons fallout models for simulating the environmental consequences of a postulated nuclear war.

Our recent activities related to atmospheric dispersion include: (1) performing experiments to evaluate the wind and temperature structure of nocturnal drainage flows in a mountain valley; (2) developing a model to incorporate a more realistic method for treating the effects of atmospheric turbulence on pollutant dispersion, and integrating a methodology to measure pollutant concentrations with the model-predicted concentration patterns; (3) evaluating model performance using the data from tracer experiments; and (4) applying our models to assess the environmental consequences of the release of radioactive materials during a postulated nuclear weapons accident.

Nocturnal Drainage Flow Experiments

We recently participated in an experiment to study how the wind and temperature structure of nocturnal drainage flows in a mountain valley are affected by the ambient meteorology. The work was performed jointly with the National Oceanic and Atmospheric Administration (NOAA) Wave Propagation Laboratory in Boulder, Colorado, and other U.S. Department of Energy (DOE) laboratories.

For this experiment, a network of meteorological towers and an acoustic sounder were operated in the Mesa Creek Valley on the north slope of the Grand Mesa in western Colorado. Analysis of the data from these instruments revealed that during periods of both clear skies and weak ambient flows above the valley, shallow nocturnal drainage flows were generated over the many individual slopes at the higher elevations. These individual flows converged at the lower elevations to form deeper flows, which then joined with flows from adjacent drainage areas. During the summer, the depths of the flows were typically a few tens of meters along the upper slopes and about 100 m over the upper part of the lower slopes. During the winter, the depths decreased to about 10 and 60 m, respectively. These flows occurred most frequently during the summer and fall months, when the ambient circulations above the valley were weak as a result of synoptic scale influences.

Because the flows along the upper slopes have minimal terrain shielding, they were particularly influenced by the ambient meteorology. When the larger-scale atmospheric flows above the valley were greater than ~5 m/s, the surface cooling along the slopes was unable to develop and maintain the surface temperature inversion needed to generate strong drainage flows. In a somewhat analogous manner, increases in atmospheric moisture led to a corresponding decrease in the radiative cooling of the sloped surfaces, which resulted in weaker down slope drainage flows than during drier conditions.

To place these observations in perspective, we used numerical models (Leone and Lee, 1989) that could account for the physical processes governing the dynamics of the flows. These models are based on solving the equations of continuity, momentum, and energy, coupled with a surface energy budget and a radiation module. The general features of the wind and temperature characteristics of the valley circulations, and the influences of strong ambient winds and atmospheric moisture on the drainage flows over the upper slopes, were well accounted for in these simulations

Model Development

Our primary modeling capability is based on our MATHEW/ADPIC models. The diagnostic wind field model MATHEW (Sherman, 1978) generates mass-consistent, three-dimensional flow fields over complex terrain using interpolated wind observations. These flow fields are used to drive our Lagrangian particle pollutant dispersion model ADPIC (Lange, 1978, 1989), which simulates the dispersion and deposition of pollutants injected into the atmosphere. Versions of our models are capable of simulating pollutant dispersion on local-to-global scales, depending on the magnitude and extent of the pollutant release. We are continually developing and evaluating these models and are using data from meteorological field experiments to increase our knowledge of the physical processes responsible for pollutant dispersion. These diagnostic wind field models also help increase our understanding of local circulations and their interactions with the larger-scale regional and synoptic flows in complex terrain.

We are now developing a new statistical pollutant-diffusion module to include in the ADPIC model. In addition, a methodology for combining pollutant concentration measurements with model predictions is being developed to improve our source-term and dose estimates. These activities will improve our capability to simulate tracer dispersion over the complete range of atmospheric boundary layer conditions. We are collaborating on this work with scientists from the Institute of Experimental Meteorology, Obninsk, and the Institute of Systems Studies, Moscow.

Turbulent Diffusion Model

To predict the temporal and spatial evolution of a pollutant released into the atmosphere, the ADPIC model calculates pseudo-Lagrangian velocities for numerous marker particles representing the pollutant. These velocities are the sum of the mean wind (derived from the MATHEW wind field model) and a diffusivity velocity related to the turbulent diffusion of the particles. The turbulent diffusion velocity is currently determined at grid points by the gradient diffusion method based on K-theory (Lange, 1978; Thomson, 1987). This relatively successful treatment (first developed for molecular turbulence) is widely used in atmospheric turbulent diffusion but is not strictly applicable under certain conditions. Its limitations have been known for some time to include cases that involve diffusion on short time scales and diabatic conditions in the atmosphere. Our goal is to implement a more realistic, fully Lagrangian, and grid-independent turbulent diffusion model that can address such conditions.

To accomplish this goal, we are investigating the performance of two other turbulent diffusion models: the random displacement model (Boughton et al., 1987) and the random velocity increment model based on the Langevin equation (Thomson, 1987). Our investigations will determine which model best simulates the release and atmospheric conditions of the major atmospheric stability regimes, which range from the convective boundary layer to the stable surface layer. If the performance of the two models is equal, the random displacement model has the advantage of requiring less computational effort; the incremental time step for the random displacement model is ten to one hundred times that for the Langevin model. Its main disadvantage is that it is not strictly valid in close proximity to the source or for convectively active boundary layer conditions, because it is based on the assumption of large turbulence time scales. The Langevin incremental velocity model, in comparison, is generally applicable to all release and atmospheric conditions. We plan to incorporate this model into the ADPIC model and to test it against theory and observations. The general form of the equation contains both a deterministic and a stochastic term. The formulation of each term is based on turbulence theory, values of turbulence statistics, and mathematical criteria. The principal component of the deterministic term is a "fading memory" of the particle velocity, whereas the stochastic term represents a closely packed series of impulses to simulate the random pressure fluctuations associated with turbulence.

The random displacement model is similar to the random walk model for describing Brownian motion. The advantage of this model is that it yields particle displacements directly, but in doing so it assumes that because of its longer time scales, most of the details described by the Langevin model during a displacement time are averaged out. We want to learn whether or not this is a good approximation during particular atmospheric conditions.

The inputs to these models, which at a minimum include the decorrelation time scale and the variance of the vertical velocity fluctuations, require continuous parameterizations involving scaling parameters for the different turbulence regimes of the boundary layer. Such values are generally available for only some boundary layer conditions. Furthermore, inconsistencies exist between parameterizations developed by individual investigators for the same stability regimes, and discontinuities exist for parameterizations at the interfaces between the various regimes. Therefore, we are also evaluating the feasibility of using large eddy simulation techniques to produce continuous parameterizations.

Integration of Measurements with Model Predictions

We are developing an automated numerical technique that will more accurately simulate the physical processes associated with pollutant dispersion in the atmosphere. This technique uses the measured pollutant concentrations in conjunction with the model-predicted concentration pattern to describe the temporal and spatial evolution of a pollutant plume. The model input parameters are varied in a selective fashion within their respective ranges of uncertainties to optimize the agreement between the measured and model-predicted concentrations. This approach involves the coupling of a nonlinear regression scheme with the MATHEW/ADPIC dispersion models to derive a best-estimate set of model input parameters related to the source term and the meteorological conditions. This set of optimal model input parameter values is calculated by minimizing the sum of the squares of the weighted residuals between the measured and model-predicted concentrations.

We investigated the numerical efficiency and robustness of several nonlinear regression schemes. We found that the method of Marquardt (Marquardt, 1963), which employs the steepest descent coupled with a Taylor-series expansion, is the most suitable for coupling with complex dispersion models that require considerable computational resources. However, the grid search with a parabolic fit method (Bevington, 1969) appears to be more advantageous for simpler (i.e., faster running) dispersion models having a small number of relatively uncorrelated parameters.

We evaluated the methodology for source term estimation using meteorological and tracer concentration data from a series of sulfur hexaflouride (SF_6) tracer experiments conducted at the Savannah River Laboratory in 1983. The experiments consisted of 14 separate tracer releases that included cross-plume concentration measurements made about 30 km from the tracer release site. By varying the meteorological parameter values of the MATHEW/ADPIC models to optimize the agreement with the measured concentrations, we were able to estimate the actual tracer release rates to a factor of 2, with the worst estimate at a factor of 5. The accuracy of this method is quite encouraging in view of the sparse tracer concentration measurements, the uncertainties associated with the spatial representativeness of the meteorological data, and the limitations of the models.

We are currently using this approach to study the uncertainties associated with the plutonium particle-size distribution resulting from an accidental high-explosive detonation of a nuclear weapon. Using meteorological and radioactivity data from a series of nuclear weapons safety tests conducted in 1963 at the Nevada Test Site, we are studying the range of particle-size distributions that will provide the best least squares agreement between the observed and computed air-concentration and surface-deposition values.

Model Evaluations

We are continually searching for experimental databases that can be used to evaluate the effectiveness of our models for simulating pollutant dispersion over various spatial scales. Over the last several years, two databases became available for testing the capability of our models to faithfully simulate dispersion processes over continental scales, and a local-scale data set became available for evaluating pollutant dispersion over complex terrain. One continental-scale data set used data from the Chernobyl nuclear reactor accident in the former Soviet Union and was provided by the International Atomic Energy Agency/Commission of European Communities/World Meteorological Organization-sponsored Atmospheric Transport Model Evaluation Study (ATMES). The other continental-scale data set was associated with the Across North America Tracer Experiment (ANATEX) conducted in the U.S. during 1987. The local-scale complex terrain data set resulted from our participation in the DOE-sponsored

Atmospheric Studies in Complex Terrain (ASCOT) field experiments. These experiments were conducted along the Front Range of the Rocky Mountains in conjunction with the EG&G Rocky Flats Plant, Winter 1991, Model Validation Experiments. The following discusses the results of these three model evaluations.

ATMES

The ATMES project focused on simulating the temporal and spatial evolution of the airborne and surface-deposited radioactivity over western Russia and Europe resulting from the Chernobyl nuclear reactor accident on April 26, 1986. This model comparison study involved simulations performed by 21 scientific institutions in Russia, Europe, North America, and Japan. Using the Russian source-term estimates and the prescribed meteorological fields provided by the World Meteorological Organization (WMO) as input to our long-range dispersion and deposition models, we computed the cesium (^{137}Cs) and iodine (^{131}I) surface-air and deposition levels at numerous sampling locations throughout Europe.

Our simulations of the total deposition over Europe were ranked the most accurate of the 21 model simulations tested, and our computed air concentrations were judged fourth in terms of agreement with the measurements. The ATMES statistical evaluation package did not confine itself to peak concentrations only but also took into account values measured at widely dispersed stations. Peak values, which are the most critical for accident situations, were well-maintained by the ADPIC model as indicated by the very good agreement on deposition. A comparison of our deposition results with the measured data is shown in Figure 1. The map indicates the overlap area between the measured and the model-predicted 2 kBq/m^2 ^{137}Cs cumulative deposition level

ANATEX

For ANATEX, chemically inert perfluorocarbon tracers were released at Glasgow, Montana, and at St. Cloud, Minnesota, and their surface-air concentrations were measured at many locations throughout the central and eastern part of the U.S. and

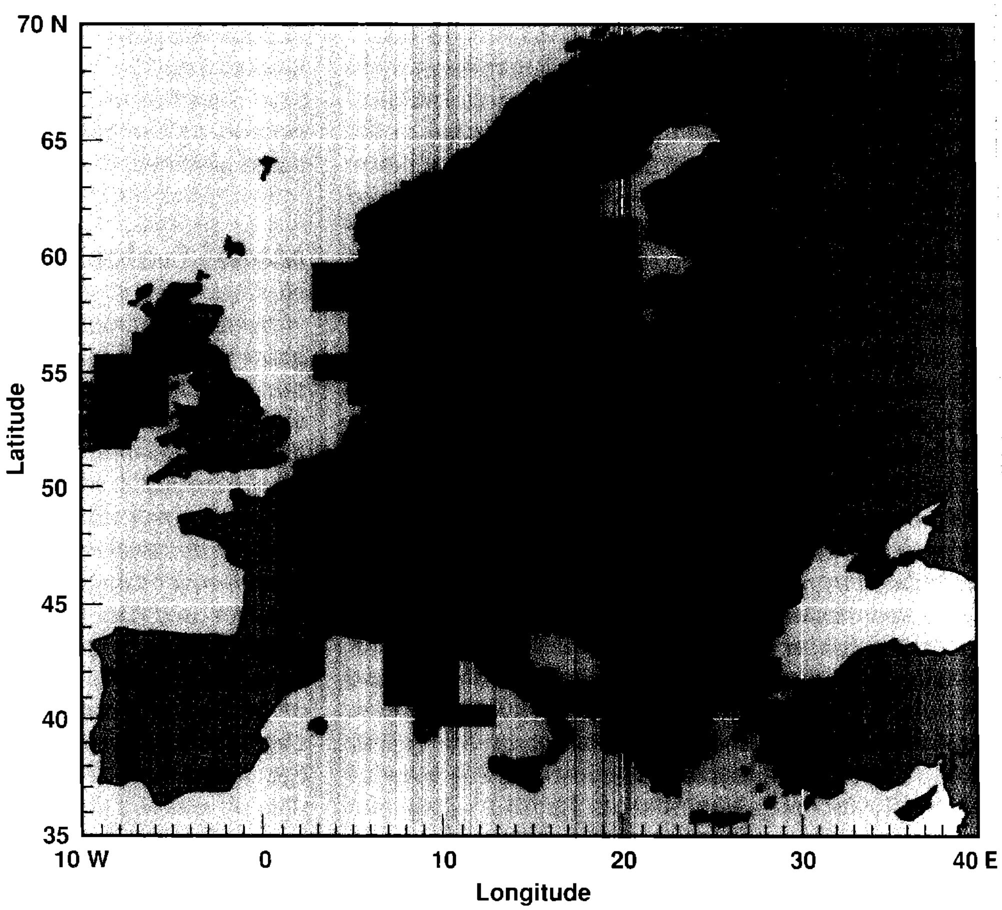

Figure 1. Measured and model-predicted 2 kBq/m^2 cesium (^{137}Cs) cumulative deposition level over the European continent 14 days after the initial release from the Chernobyl nuclear reactor accident on April 26, 1986. The light orange region is the measured deposition, the yellow region is the model-predicted deposition, and the dark orange region is the overlap area.

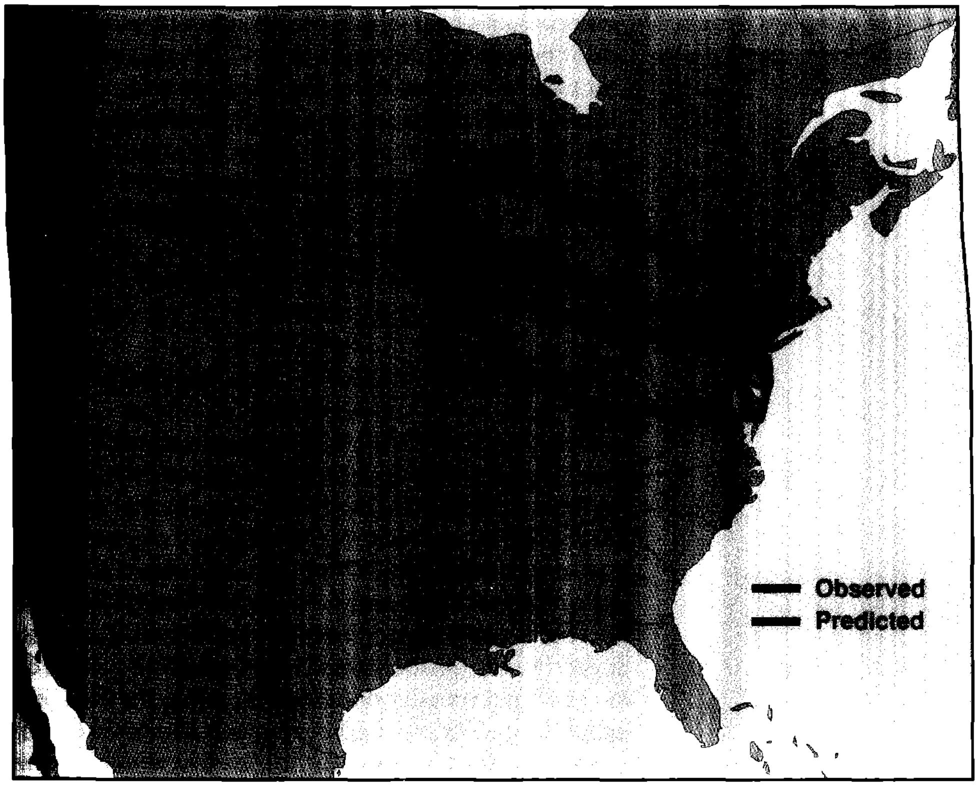

Figure 2. Boundaries of the observed and model-predicted plumes following the release of chemically inert perfluorcarbon tracers at Glasgow, Montana, on January 10, 1987. The boundaries circumscribe the areas of elevated tracer concentrations during the 48–72 hr period after the release. The bounded areas are similar in size, indicating that the diffusion process simulations were reasonably accurate. The misalignment of these two areas, however, suggests that the wind data input was insufficient.

Canada. We are now evaluating the ability of the hemispheric-scale Lagrangian particle (HADPIC) model to estimate the resulting surface-air concentrations of the tracers out to distances of about 3000 km from the release points. Some of these evaluations have led to a number of model enhancements that include a more accurate turbulence parameterization for long-range diffusion, the addition of "curvature" terms to the atmospheric flow description that improved plume trajectories, and a more realistic spatial interpolation of wind observations near the surface.

Figure 2 shows an example of our model simulation of the 3-hr tracer release that occurred on January 10, 1987 at Glasgow, Montana. The boundaries of the model-predicted tracer plume, as defined by 24-hr averaged concentrations, are compared to the boundaries of the observed plume during the 48 to 72 hr period after the release. Note that although the predicted and observed plume dimensions are similar in area, the patterns are not properly aligned. This suggests that, although the model was able to reasonably simulate the diffusion processes, the spatial and temporal resolution of the observed winds may have been too coarse for geographical alignment of the predicted and observed plumes.

ASCOT

For the ASCOT field experiments, we participated with scientists from other DOE and NOAA laboratories in a series of meteorological and tracer experiments along the Front Range of the Rocky Mountains near Boulder, Colorado. The purpose of these experiments was to provide the data needed to characterize and predict local and regional circulations over complex terrain, and to apply these data to the development and evaluation of pollutant dispersion models. SF_6 was released from the EG&G Rocky Flats Plant, and the downwind air concentrations were measured out to a distance of 16 km. These experiments were supported by an array of meteorological measurement systems that included tower-mounted instrumentation, sodars, rawinsondes, tethersondes, microwave wind profilers, and a lidar.

The resulting databases were used to evaluate the ability of the MATHEW/ADPIC models to simulate pollutant dispersion within the multilayered flows observed during the experiments. A model simulation of one of the nighttime releases from the Rocky Flats Plant is shown in Figure 3a. The ADPIC marker particle distribution indicates the location of the released SF_6 tracer at 0300 MST on February 5, 1991. Figure 3b shows a

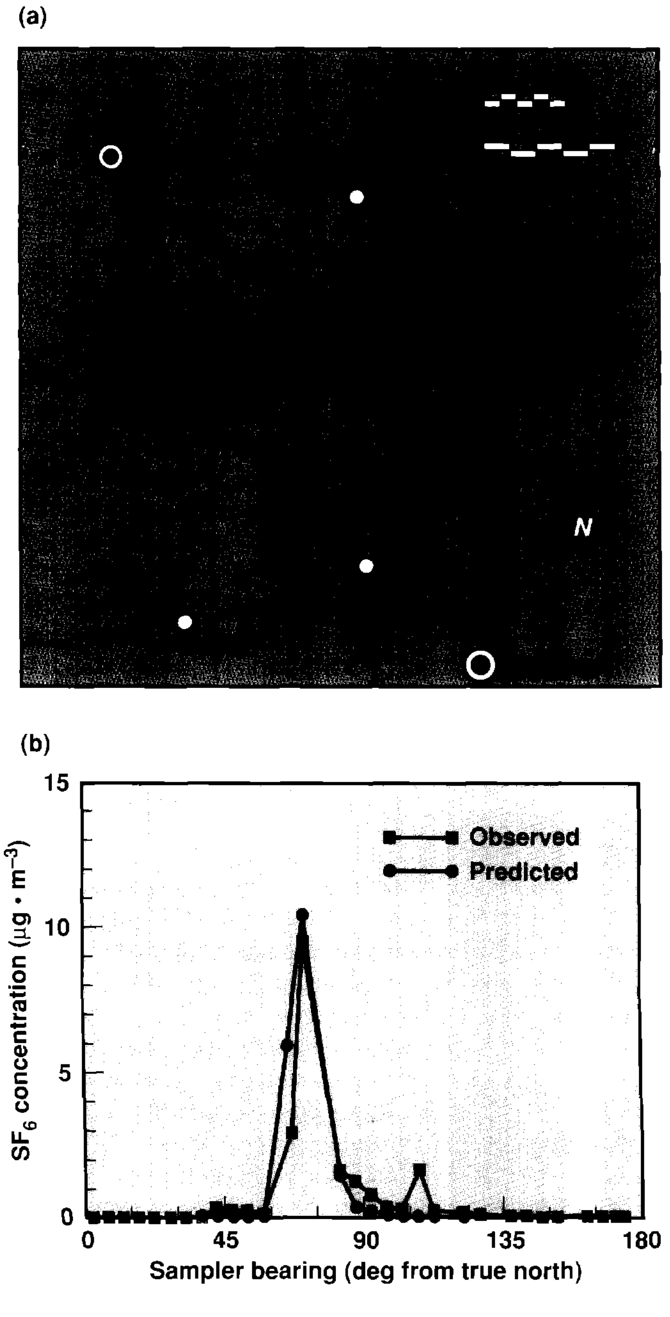

Figure 3. (a) Results from a model simulation of a continuous nighttime release of sulfur hexafluoride (SF_6) from the EG&G Rocky Flats Plant on February 4–5, 1991. The ADPIC marker particle distribution shows the plume at 0300 MST on February 5, 1991. The cross-plume sampling arc (heavy solid line) is about 16 km east of the tracer release point. (b) A comparison of the model-predicted and observed tracer concentrations along the cross-plume sampling arc shows our simulations to be in good agreement with the observed concentrations.

comparison of the observed and model-predicted tracer concentrations along a cross-plume sampling arc located 16 km east of the tracer release point. This simulation, which used a meteorological database to define the three-dimensional wind fields of the boundary layer, is in excellent agreement with the tracer observations. Measurements and computations indicated that the bulk of the tracer was confined within the first 100 m above the surface under the nighttime conditions.

Model Applications

We have combined our source term models and atmospheric dispersion and deposition models with meteorological, radiological dose, and population databases to develop a probabilistic consequence assessment capability. This capability allows us to estimate the environmental consequences of potential nuclear weapons accidents during which hazardous materials are injected into the atmosphere. The accidents of primary concern are explosions and fires engulfing nuclear weapons systems. We have considered accident scenarios for cases in which the weapons system is being stored, serviced, and transported. Because criticality or supercriticality may potentially occur, we are concerned not only with the dispersal of weapons materials such as plutonium (^{239}Pu) and uranium (^{235}U), but also with fission products and tritium.

Hazard assessments of such accidents must include the consequences associated with the multiple pathways that may lead to human exposure. The most likely pathways include direct exposure to the passing radioactive cloud and the resulting surface contamination; inhalation of resuspended radioactivity; and the uptake of activity into foodstuffs through various terrestrial pathways. In addition to estimating human exposure, the models can be used to estimate the cost-effectiveness of proposed mitigation measures for reducing health and environmental impacts.

Over the past year, we have completed a variety of consequence assessments associated with postulated accidents. For example, we recently completed an assessment of a hypothetical weapons accident caused by the ignition of propellant in a missile silo. This accident, which was assumed to occur near the center of a missile field, resulted in the dispersion of ^{239}Pu into the environment. The inhalation dose resulting from direct exposure to the plutonium-bearing cloud is indicated by the exposure pattern shown in Figure 4a. By integrating this exposure pattern across the population distribution, we obtained the probability distribution for exceeding specific population dose levels (Figure 4b).

This probabilistic consequence assessment considers not only the accident scenario and location, but also the local wind patterns, population distribution, and the shelters available to the resident population. These data can be used to estimate the health risk to current and future populations in the affected areas.

RADPATH: Biogeochemical Pathways of Artificial Radionuclides

We participated in an international effort to study the behavior of radionuclides in the environment. The RADPATH project was initiated in June 1988 to study the biogeochemical pathways of artificial radionuclides and is under the auspices of the Scientific Committee on Problems of the Environment (SCOPE), a standing committee of the International Council of Scientific Unions. This work was motivated by the desire to learn as much as possible from the Chernobyl releases and is a follow-on to the SCOPE-ENUWAR project that studied the environmental consequences of nuclear war, which we also contributed to significantly.

Through a series of international workshops, the SCOPE-RADPATH project has sought to elucidate the environmental pathways of artificial radionuclides following releases from the nuclear fuel cycle, reactor accidents, spills, and the detonation of nuclear weapons. These findings are being applied to advance our understanding of biogeochemical cycling, which is the transfer of substances among the terrestrial ecosystems, the oceans, and the atmosphere through interactive physical, chemical, and biological processes. A primary objective of RADPATH is the publication of an overview, that is comprehensible to scientists not having specialized knowledge of the field, and that includes the most significant sources and environmental pathways of radionuclides released as a result of human activities. The book is expected to be published in 1992 by John Wiley & Sons, Inc., as part of the SCOPE series of technical books, and will cover the following topics: sources, case studies, atmospheric transport, terrestrial pathways, aquatic pathways, urban environment, dosimetry, and the assessment of environmental effects.

(a)

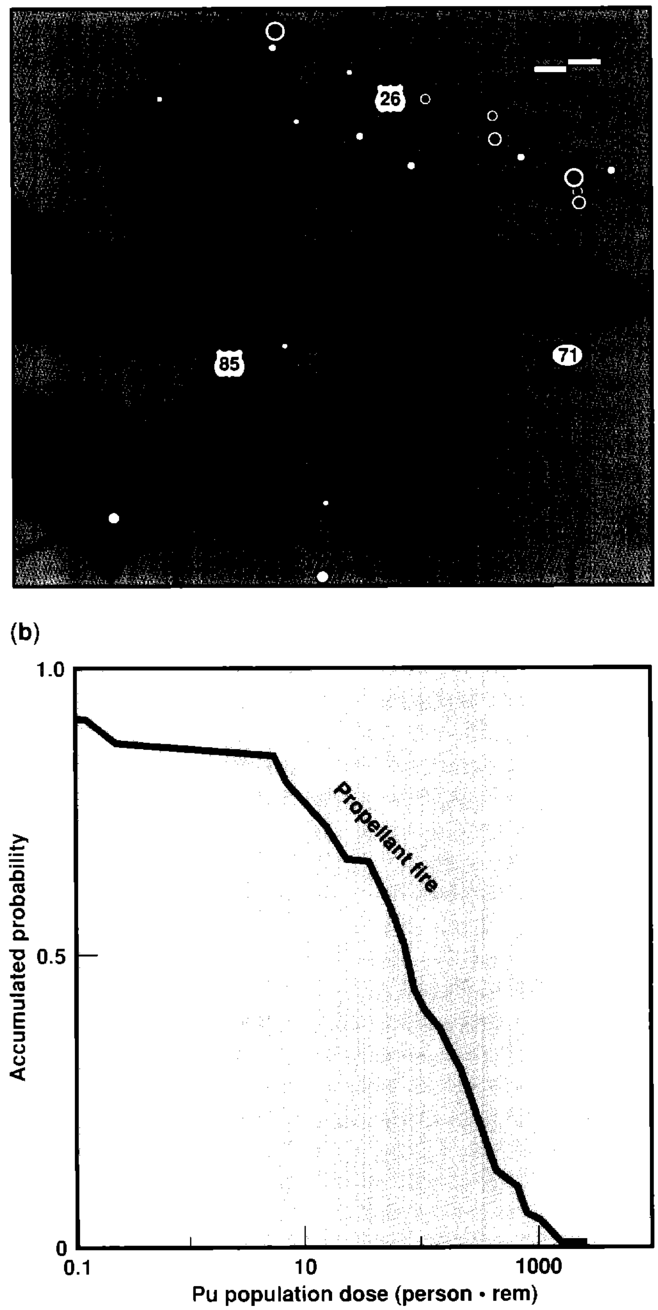

Figure 4. (a) Results from a model simulation of the potential environmental consequences associated with a postulated nuclear weapon accident involving a propellant fire in a missile silo. The green regions are Peacekeeper basing zones; the blue regions indicate the exposure pattern of plutonium inhalation dose isolines from direct cloud exposure; and the circles represent population centers. In the probabilistic accident analysis, it was equally likely for the fire to occur in any one of the three basing zones shown. (b) The probability distribution for exceeding specific plutonium population dose levels is derived from the integration of the exposure pattern with the population distribution.

Future Plans

On the experimental side, we will continue to participate in multilaboratory field experiments so that we can acquire the data needed for our model development and evaluation activities. Our activities will continue to involve scientific collaboration with other DOE and NOAA laboratories, and we plan to broaden our collaboration with scientists within the Commission of European Communities (CEC) and Russia. We hope our participation with the CEC in the future will serve as a vehicle for mutual collaboration in model development and evaluation, thereby strengthening our respective emergency response capabilities.

On the modeling side, we will continue to improve our three-dimensional local-scale wind field model, and we will incorporate a more realistic statistical turbulent diffusion module into the ADPIC dispersion model. Our model development activities will be closely associated with the development of a forecast modeling capability that is suitable for emergency response applications. These advanced modeling capabilities will be integrated into the existing Atmospheric Release Advisory Capability (ARAC) emergency response system, which supports the DOE and U.S. Department of Defense emergency preparedness programs, and into the emerging Probabilistic Consequence Assessment Capability, which is a new method of consequence assessment based on investigating probable accident scenarios.

Group Members

The work described in this article was performed by, or under the auspices of, the Model Applications and Nuclear Effects Group. Scientists involved include Paul H. Gudiksen (Group Leader), Richard T. Cederwall, Phil B. Duffy, Leslie L. Edwards, Ted F. Harvey, Rolf Lange, Leonard A. Lawson, R. Miki Moore, Linda G. Peters, Howard C. Rodean, Dan J. Rodriguez, and Charles S. Shapiro.

We are participating with a number of researchers from other laboratories, universities, and institutes whose contributions may not be fully reported here. Appendix B gives a summary of these interactions.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division; the Department of Energy, Office of the Under Secretary, Office of Arms Control and Nonproliferation; the Department of Energy, Assistant Secretary for Defense Programs; and the Department of Defense, U.S. Air Force.

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Understanding Why Climate Models Agree and Disagree

W. Lawrence Gates, Program Director

The Program for Climate Model Diagnosis and Intercomparison conducts a program of systematic numerical experimentation and model intercomparison to promote climate model improvement and increased cooperation among modeling groups.

The DOE's Environmental Sciences Division established the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at LLNL in late 1988. PCMDI's charter is to address (1) the persistent significant and unexplained differences in the climates simulated by different atmospheric general circulation models (GCMs), and (2) the uncertainty that these differences introduce into the reliability of the models' simulations of possible future regional climate changes due to increasing carbon dioxide (CO_2) and other greenhouse gases. The long-range goal of PCMDI is to understand and reduce the causes of climate model errors. PCMDI is located in a dedicated facility that houses 20 atmospheric research and computations staff and a network of Sun workstations connected to supercomputers of the National Energy Research Supercomputer Center (NERSC). The primary objectives of PCMDI, consistent with the above goals, are to

- Promote climate model improvement through the development of standards in model design, simulation, validation, diagnosis, and intercomparison.
- Carry out a systematic program of numerical experimentation with representative climate models in order to (1) establish the sensitivity of global and regional climate to model formulation and parameterization, and (2) characterize the climate's natural variability and predictability on seasonal to centennial time scales.
- Develop innovative software for the analysis, diagnosis, and visualization of climate data.
- Develop a comprehensive model-oriented climatological database.
- Promote increased cooperation among climate modeling groups.

PCMDI's current strategy for reaching these objectives is a two-pronged approach. The first approach is to conduct modeling studies using the global atmospheric forecast models of the European Centre for Medium Range Weather Forecasts (ECMWF), under a cooperative agreement with that institution. Studies with the two versions of the ECMWF GCM currently in use at PCMDI include (1) analysis of the models' systematic errors and their natural variability in interannual climate simulations, and (2) studies of the dependence of the models' portrayals of the atmospheric circulation and the heat and moisture balances on model resolution. Highlights of this and related research are given below, along with a brief description of PCMDI-developed software.

A second research approach stems from PCMDI's leadership and coordination of international climate-model intercomparison and diagnostic activities. These projects include the Atmospheric Model Intercomparison Project (AMIP), which is initially evaluating model simulations of the period from 1979 to 1988, and the Feedback Analysis for GCM Intercomparison and Observations (FANGIO), which is comparing the strengths of selected feedbacks in atmospheric models.

Atmospheric Model Resolution Studies

Predicting regional climate change is the overall focus of the U.S. Global Change Research Program. An important question addressed by this program concerns the spatial resolution of models needed to make such projections. Diagnosis of a suite of 15-month integrations with the ECMWF model at resolutions T21, T42, T63 and T106 (about 5°, 3°, 2°, and 1° resolution in latitude and longitude) has formed the basis of extensive PCMDI analyses of horizontal-resolution effects on model-simulated climate. In general, these studies show that the large-scale climate simulated at T21 is distinctly different from that seen with higher-resolution versions of the model; however, the large-scale character of the simulated climate changes relatively little as the resolution is refined from T42 to T106 (i.e., from about 3° to 1° resolution) (Gates et al., 1992). This point is illustrated by the results shown in Figure 1 for the distribution of July precipitation. Similar results have been found for the large-scale distribution of such variables as sea-level pressure and temperature. In Figure 1, the simulation at highest resolution (T106) is little changed from that at lower resolutions (excluding T21), indicating that the model's large-scale systematic errors are not significantly reduced by increases in resolution alone. The observed climatological July precipitation, for example, shows a single maximum of precipitation over Indonesia rather than the double maximum on each side of the equator seen here.

Figure 2 shows another example of the ECMWF model's systematic errors. The mean annual heat exchange at the ocean surface is shown as given by the model at T106 resolution and as observed (Gleckler and Taylor, 1992). Although the large-scale patterns of observed and simulated results are similar, the model is seen to significantly overestimate the heat exchange in nearly all regions. Analyses of this type for the various components of the surface heat exchange provide valuable evidence of the nature and source of the model's errors and indicate where improvements could be made.

In addition to conducting resolution studies with the earlier version (cycle 33) of the ECMWF model, we are examining the results of a newer version (cycle 36). Figure 3 shows the zonally averaged vertical velocity simulated for July in both model versions (Boyle, 1992). The separate bands of rising motion near 10° N and 10° S in the earlier model (Figure 3a) with T42 resolution corresponds to the double-cell structure of precipitation seen in Figure 1, while this (erroneous)

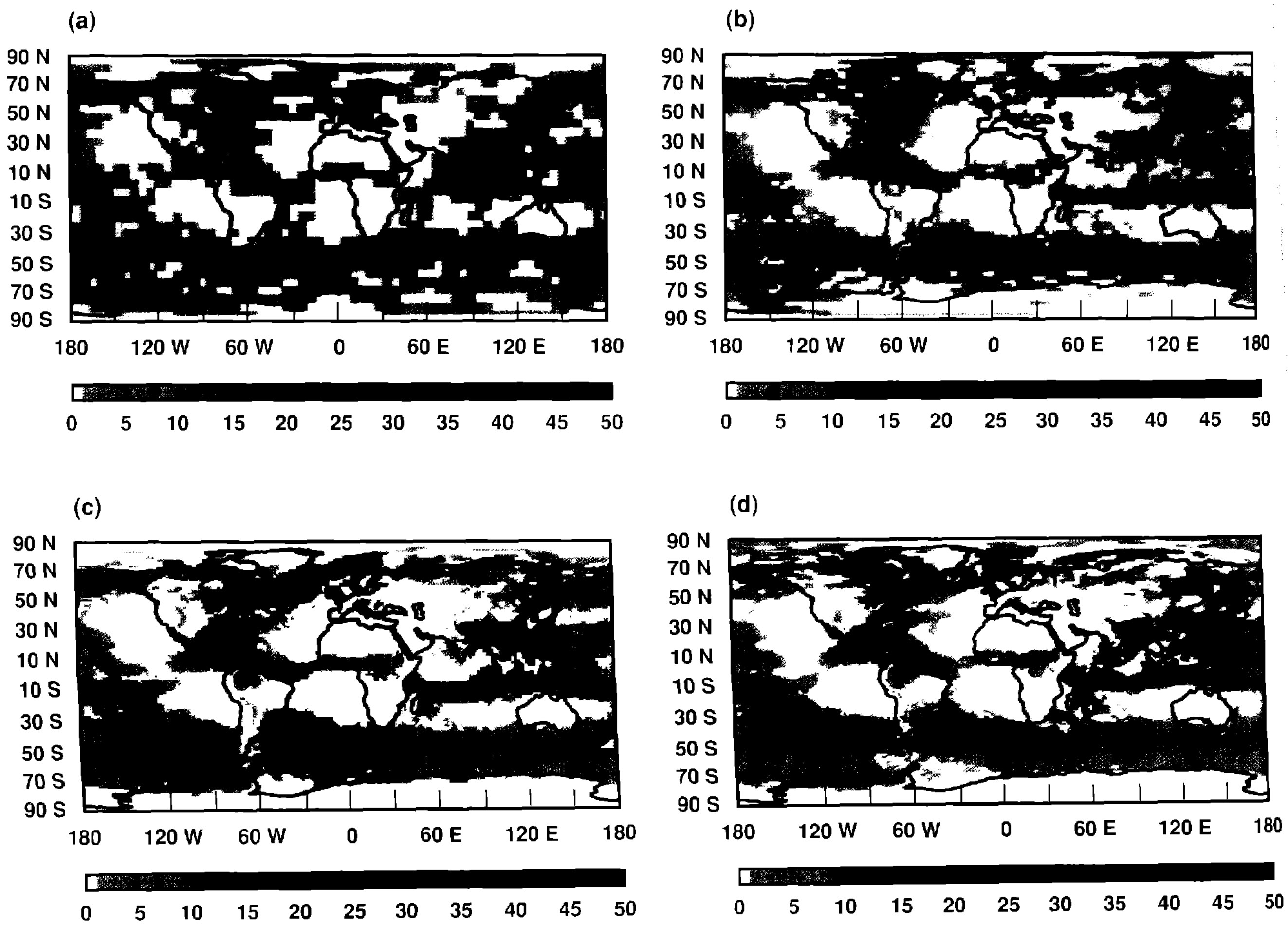

Figure 1. July precipitation (mm/day) simulated by the ECMWF model at horizontal resolutions **(a)** T21, **(b)** T42, **(c)** T63, and **(d)** T106 (from Gates et al., 1992).

feature is absent in the results of the newer version (Figure 3b). This improvement was the result of reformulating the parameterization of surface evaporation to provide a larger vertical heat flux under conditions of low wind speed over the tropical oceans. The circulation shown in Figure 3b resembles that observed and again illustrates the value of diagnostic calculations in documenting model improvement.

Although the results shown in Figures 1 through 3 are representative of the ECMWF model's time-averaged behavior, there is considerable variability on synoptic time scales. Using high-resolution (T106) perpetual seasonal integrations of the earlier model version, we simulated the time-longitude behavior of outgoing July long-wave radiation near 7° N (see Figure 4). Lower values in the figure represent higher convective activity. The model is seen to simulate westward-moving convective bands over the ocean with a phase speed close to that observed. Diurnal convective activity is seen near 70° W over South America, while spatially coherent convective episodes of lower frequency are seen over the Atlantic and Pacific Oceans. In January, these fluctuations are

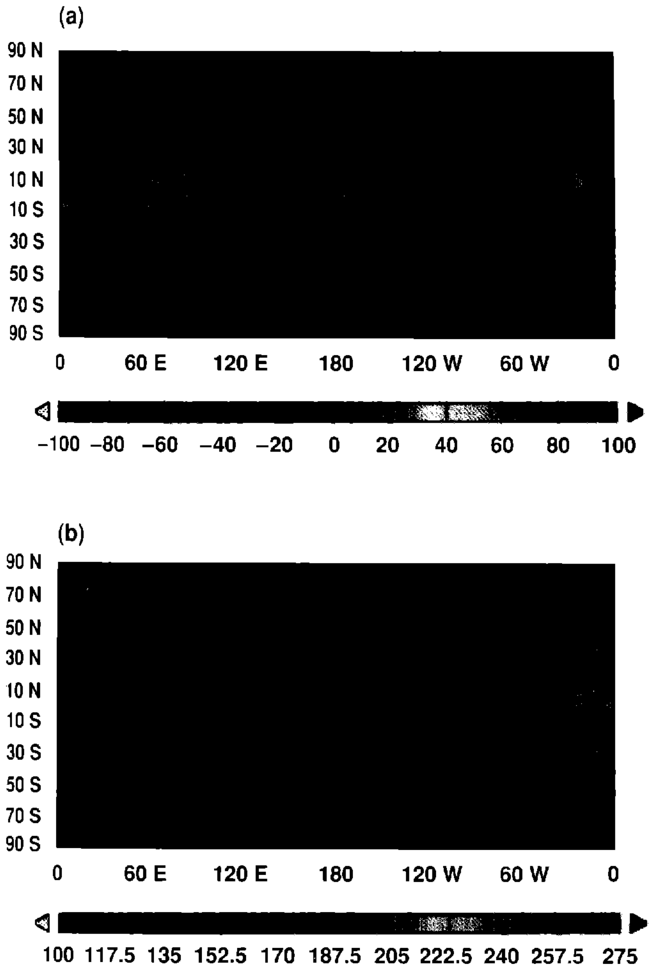

Figure 2. Annual net energy flux (W/m^2) at the ocean surface as **(a)** observed, and **(b)** simulated by the ECMWF model at T42 resolution (from Gleckler and Taylor, 1992).

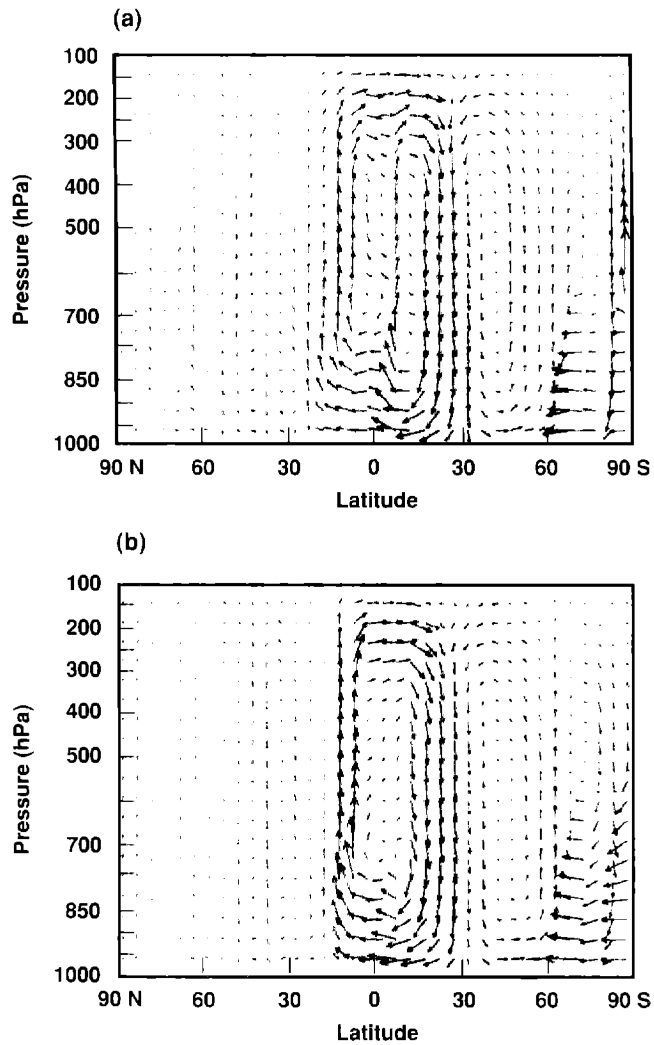

Figure 3. Zonally averaged July circulation in the meridional-vertical plane simulated by the ECMWF model. **(a)** Cycle 33, **(b)** cycle 36 (from Boyle, 1992).

more episodic, and lower-frequency variability is prevalent over the eastern hemisphere, like that seen in the analysis of satellite observations.

Ocean Model Resolution Studies

In parallel with PCMDI's atmospheric model resolution study, we have conducted a study using an oceanic GCM that includes realistic bottom topography and basin geography over the globe. With this model, we have simulated the present-day ocean climate using latitude/longitude grid spacings ranging from 1/2° × 1/2°, which approaches the spatial extent of mesoscale eddies, to a coarse 4° × 4°, which is often used in climate models that incorporate oceans. This study addresses the question of whether resolution of smaller-scale circulations is necessary to correctly simulate the large-scale ocean climate. Results of this preliminary experiment indicate that large-scale ocean circulation is generally insensitive to grid spacings less than about 2° × 2°. If confirmed by more detailed analyses and by simulations allowing ocean interaction with the atmosphere, this conclusion would support those of earlier studies—which are based on simplified circulation models—that mesoscale ocean eddies make little net contribution to poleward heat transport by the oceans.

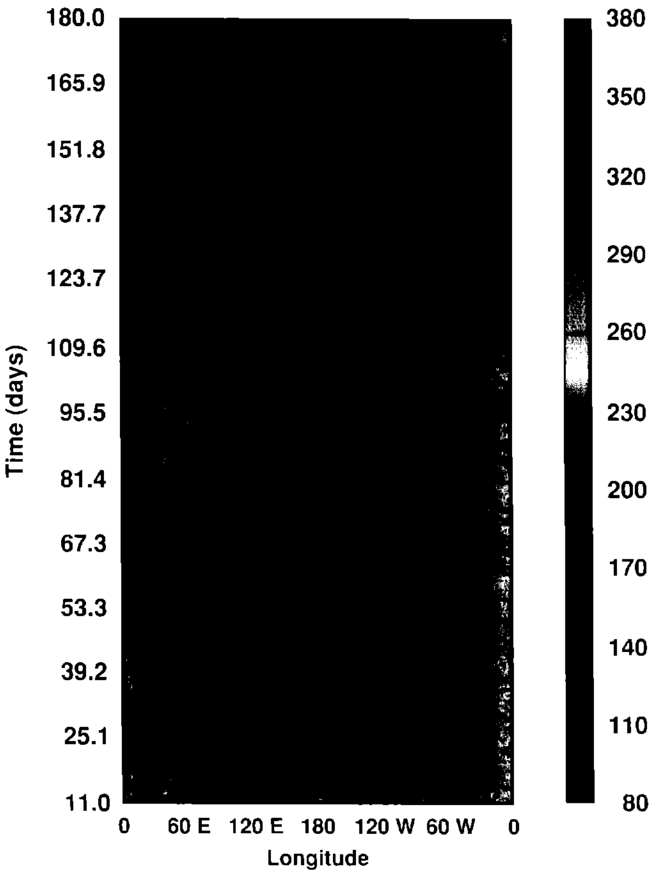

Figure 4. Outgoing long-wave radiation (W/m^2) at 7° N as a function of time and longitude during a perpetual-July simulation with the ECMWF model at T106 resolution (from Slingo et al., 1992).

Atmospheric Model Intercomparison Project

In collaboration with the international climate modeling community, PCMDI is leading the most comprehensive intercomparison of atmospheric models yet undertaken in order to establish standards for climate-model evaluation (Gates, 1992). Known as the Atmospheric Model Intercomparison Project (AMIP) and coordinated through the Working Group on Numerical Experimentation of the World Climate Research Programme, this project calls for all global atmospheric models to be integrated over the decade 1979–1988 using the observed monthly-averaged distributions of sea-surface temperature and sea ice especially prepared for this purpose (PCMDI, 1991) and with standard values of the solar constant and atmospheric CO_2 concentration. Figure 5 gives an illustration of the ocean surface boundary conditions assembled for AMIP. An agreed-to set of output quantities is to be calculated by each model and placed in a common storage format at PCMDI to facilitate analysis.

At present, there are 28 organizations participating in AMIP (see Table 1), of which 13 have already completed the required integrations. In addition to taking the lead role in the summary of the overall model results, PCMDI is organizing a set of AMIP subprojects in which advanced diagnoses will be made of specific aspects of the models' performance, such as the simulation of tropical variability, monsoons, storm tracks, hydrology, and cloud-radiative forcing. AMIP participants are being encouraged to participate in these subprojects and to propose others according to their interests.

Intercomparison of Feedback Mechanisms

PCMDI is also supporting an international project called Feedback Analysis for GCM Intercomparison and Observations (FANGIO), which is being carried

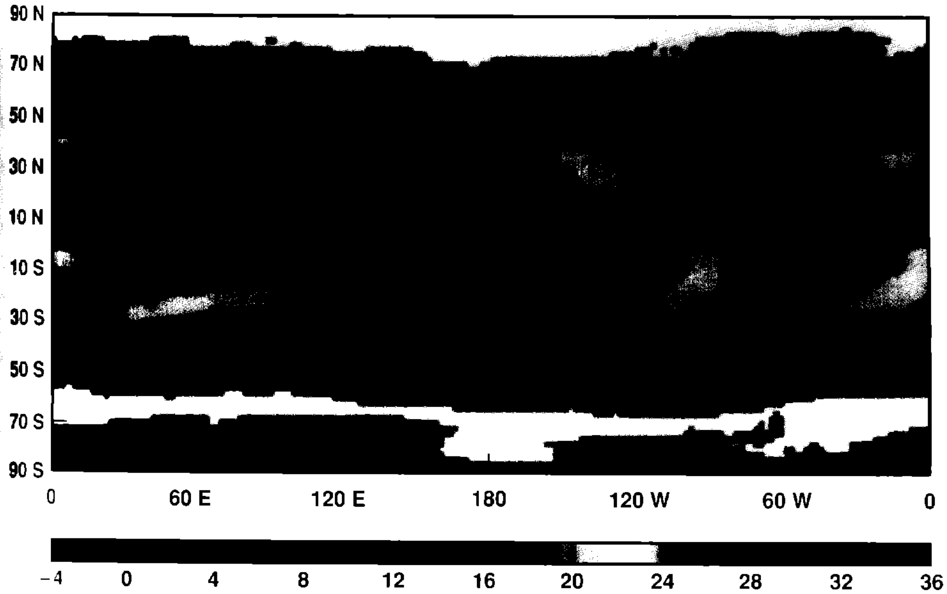

Figure 5. Average distribution of sea-surface and sea ice temperature (°C) observed during September 1982, as compiled for use in AMIP (from PCMDI, 1991).

able 1. Organizations participating in the Atmospheric Model Intercomparison Project (AMIP).

rganization	Country
cademy of Sciences	Russia
ureau of Meteorology Research Centre	Australia
anadian Climate Centre	Canada
entre National de Recherches Meteorologiques	France
olorado State University	U.S.
ommonwealth Scientific and ndustrial Research Organization (CSIRO)	Australia
uropean Centre for Medium Range Weather Forecasts	U.K.
eophysical Fluid Dynamics Laboratory	U.S.
oddard Institute for Space Studies	U.S.
oddard Space Flight Center	U.S.
ydrometeorological Centre	Russia
stitute of Atmospheric Physics	China
pan Meteorological Agency	Japan
boratoire de Meteorologie Dynamique	France
os Alamos National Laboratory	U.S.
ain Geophysical Observatory	Russia
arshall Space Flight Center	U.S.
ax Planck Institute for Meteorology	Germany
eteorological Research Institute	Japan
ational Center for Atmospheric Research	U.S.
ational Meteorological Center	U.S.
aval Research Laboratory	U.S.
ate University of New York at Albany	U.S.
nited Kingdom Meteorological Office	U.K.
niversity of California at Los Angeles	U.S.
niversity of Illinois at Urbana/Champaign	U.S.
niversity of Maryland	U.S.
niversity of Reading	U.K.

out with DOE support. This project is led by Robert Cess of the State University of New York at Stony Brook, who serves as a consultant to PCMDI. This project has shown that current climate models display a wide range of sensitivity owing to their treatment of clouds and cloud feedback, as shown in Figure 6 for 19 GCMs. In an attempt to determine which model is producing the most nearly "correct" result, the FANGIO project is validating the results with data from the Earth Radiation Budget Experiment (ERBE). A newly devised comparison method, which takes into account the ERBE observing method and its generation of "missing" data, will result in a more realistic evaluation of model-generated cloudiness and radiation (Cess et al., 1992).

A second set of perpetual-season runs in FANGIO is focused on snow-feedback processes, with each model being run with and without a fixed snow cover for the month of April. The results indicate that amplification or moderation of snow-cover forcing may be caused by both cloud interactions and long-wave radiation. For example, in one model we found that the melting of snow is accompanied by a local increase in cloud cover such that the reduction of surface albedo is almost exactly compensated by the higher albedo of clouds. The net result is an insignificant snow feedback in the model. Other models give a spectrum of results, and a paper has been published summarizing the differences among models and the interactive nature of cloud and snow feedback (Cess et al., 1991).

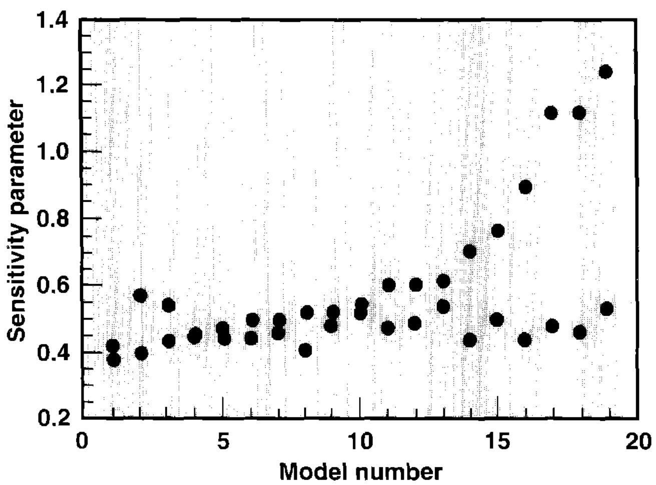

Figure 6. Response of 19 atmospheric models to changed sea-surface temperature under clear-sky conditions (black circles) and cloudy conditions (blue circles), as found in FANGIO perpetual-July simulations (from Cess et al., 1990).

Studies of Climate Variability and Model Analyses

We have conducted empirically based studies of the relationship between precipitation in northeastern Brazil and sea-surface temperatures in the tropical Pacific and Atlantic Oceans. These studies have revealed that the sea-surface temperatures modulate the variations in precipitation and that the time scales of variation are phase-locked (Sperber and Hameed, 1992). These observed phenomena may be used to validate extended integrations of GCMs, such as those being performed in AMIP. Related studies of the influence of horizontal resolution on the simulation of the Indian monsoon and North American precipitation in the ECMWF model support the conclusion that the model mean fields are generally quite similar (with the exception of the lowest resolution employed), but show that the spectrum of higher-frequency (synoptic) fluctuations are resolution dependent on local and regional scales.

To evaluate time sampling errors in model analyses, we carried out a special 60-day perpetual July simulation using the ECMWF GCM. At every hour of the integration, radiative fluxes were calculated and fields of selected surface and atmospheric fields were saved, yielding a detailed history of the diurnal cycle of model climate. We found that the first- and second-moment climate statistics of most variables in the free atmosphere can be adequately estimated by sampling only a few times per day, but that the surface variables and convective processes that are strongly influenced by the diurnal cycle require more frequent sampling—ideally at intervals that are nonintegral divisors of a 24-hr day (such as at 5- or 7-hr intervals) to reduce aliasing errors (Phillips et al., 1992).

To promote the systematic analysis of climate model simulations, PCMDI is developing a comprehensive computerized database of model properties, together with references to the models' use and validation. In a hypertext format (implemented in Macintosh Hypercard), this database includes information on virtually all of the world's atmospheric GCMs. A supplemental relational database (implemented in Oracle) focuses on those models participating in specific intercomparisons. These databases permit the rapid survey of models by version, author and model property, and will be made available to the climate modeling community.

To promote model analysis, we are also in the process of building a comprehensive assembly of observed atmospheric data. This observational database is intended to contain all available global gridded data sets for such variables as temperature, geopotential, wind, humidity, precipitation, and cloudiness in terms of monthly, annual, or interannual averages. This database will be an invaluable resource for model validation and intercomparison.

Data Storage and Display Software

In 1991 we completed development of the DRS (Data Retrieval and Storage) data-management system. DRS is a system of libraries and utilities that support the standard machine-independent file format in use at PCMDI. DRS has a number of features that make it especially suited for the storage and access of climate modeling data. The utilities support interactive graphics, browsing through data files, and file-format translation for importing into DRS. This system has been received enthusiastically by the institutions to which it has been ported, and it is available to all groups engaged in climate research. This software library exists both on local work stations and on the NERSC Cray computers to facilitate data manipulation and display.

PCMDI has also developed a graphics application that uses the DRS library. It consists of an interactive interface for selecting data and has the capability to display a two-dimensional variable using labeled isolines and/or color fill between isolines. The color table can be manipulated interactively and the results seen immediately. Sequences of these displays can be generated, saved, and then played back in a "movie" mode.

The development of postprocessing programs is also an important PCMDI activity, especially in connection with AMIP. We have developed a program to calculate time-averaged fields on pressure surfaces and to calculate the velocity potential, stream function, and other derived quantities from the model output. We have also developed an additional history-of-state postprocessor to produce the standard output variables for AMIP.

Future Efforts

Over the next few years, PCMDI's plans are to (1) continue support of the AMIP effort and its associated diagnostic subprojects, (2) actively support attempts to assemble model-consistent validation data, and (3) develop a comprehensive model diagnostic library. As a result of this work, PCMDI will be in a position to prepare authoritative and comprehensive analyses of model errors that should be useful in the interpretation of model sensitivity and performance tests. PCMDI also plans to conduct exploratory studies of climate variability and predictability with coupled global atmosphere–ocean models.

PCMDI's efforts to develop community standards for the storage, retrieval, and display of massive amounts of climate data are important adjuncts to its modeling research. This aspect of our work will continue to receive high priority, as will our support of advanced methods of computation and visualization.

Group Members

The work described in this article was performed by, or under the auspices of, the Program for Climate Model Diagnosis and Intercomparison. Members of this group include W. Lawrence Gates (Program Director), James S. Boyle, Lisa C. Corsetti, Curtis C. Covey, Clyde G. Dease, Robert S. Drach, Peter J. Gleckler, Stanley L. Grotch, Ambrosio R. Licuanan, Robert L. Mobley, Thomas L. Phillips, Gerald L. Potter, Benjamin D. Santer, Sailes K. Sengupta, Kenneth M. Skinnell, Kenneth R. Sperber, John L. Stout, Karl E. Taylor, and Dean N. Williams.

PCMDI staff are participating with researchers from other laboratories, universities, and institutes whose contributions may not be fully reported here. Appendix B provides a brief summary of these collaborations.

Sponsoring Organization

This work has been supported by the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division.

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The Local and Regional Role of Clouds

Marvin H. Dickerson, Group Leader

The Cloud Modeling and Experiment Support Group develops and applies cloud and radiative transfer models to study the life cycles of cumulus and other cloud types. We also lead the experiment support activities for DOE's ARM program.

The newly formed Cloud Modeling and Experiment Support Group evolved from the cloud modeling work begun in G-Division during the 1970s and from our more recent involvement in experiment support activities for the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program.

The current focus in cloud modeling is on developing and applying three-dimensional nonhydrostatic cloud models with microphysics and radiative transfer parameterizations to problems associated with cumulus and other cloud life cycles and to cloud-climate feedback processes. We use these models to study cloud systems ranging from mid-latitude thunderstorms to tropical western Pacific, deep convective storms. Results of some of these studies and of the cloud modeling work associated with nuclear winter studies are described in this article.

Our experiment support activities for the ARM program focus on defining and implementing the requirements for conducting an atmospheric science experiment. These requirements include (1) developing, testing, and implementing algorithms that can transform observational data from field instruments into measurements used for modeling, (2) developing models that can simulate the observations made by particular instruments, (3) developing models to evaluate parameterizations of atmospheric physical processes, and (4) coordinating the cloud research of scientists at several institutions across the United States. These experiment support activities provide a more formalized and systematic approach for linking modeling activities and field observations than was available before the ARM program.

Cloud Modeling

The Cloud Modeling and Experiment Support Group is conducting a wide range of research on cloud-related atmospheric processes, from the almost instantaneous scavenging of submicron aerosol particles by growing cloud droplets, to the dynamics of severe thunderstorms, to the long-term effects of tropical cirrus anvils on global climate. During the last five years, our research activities have focused on developing unique modeling capabilities and participating in several interagency research programs. The modeling of cloud dynamics, microphysics, and radiation interactions has become a vital component of G-Division's capability to address major, multiscale atmospheric issues.

For more than twenty years, in support of DOE and U.S. Department of Defense programs, we have conducted cloud physics and precipitation scavenging research. Our earliest research addressed the fate of small amounts of radioactivity released by nuclear tests at the Nevada Test Site. These investigations led to a comprehensive study of the possible collateral damage associated with the potential for precipitation scavenging of radioactive debris from tactical nuclear weapons (Crandall et al., 1973; Knox and Molenkamp, 1974; Knox et al., 1975; Molenkamp, 1977). As a result of this research, military plans associated with the contingent employment of tactical nuclear weapons were modified. We also postulated and investigated the phenomenon of self-induced rainout (the scavenging of radioactive debris from nuclear weapons by precipitation that could develop as a result of the detonation itself or the fires ignited by the blast). We demonstrated that self-induced rainout may have occurred in Hiroshima and probably occurred in Nagasaki (Molenkamp, 1980).

During the 1980s, we began studying natural cloud processes. In one study, we used a numerical cloud model, along with observations provided by the British Meteorological Office, to simulate orographic storms (storms triggered by hills and mountains) over the Glamorgan Hills of South Wales. We showed that mountain wave dynamics were largely responsible for the previously unexplained high sensitivity of cloud microphysical processes and rainfall rates to wind speed (Bradley and Wilhelmson, 1984).

Modeling Clouds and Smoke from Very Large, Intense Fires

Our more recent cloud physics research has focused on the global consequences of a large-scale nuclear exchange. We used a mesoscale model, two numerical models, and a detailed microphysical model to investigate the atmospheric injection and precipitation scavenging of smoke from the very large, intense fires that would be ignited during such an exchange.

In our earlier studies, using a two-dimensional cloud model, we concluded that large city fires would trigger the formation of convective clouds and that a significant fraction of the smoke particles could be scavenged by growing water droplets in the clouds (Bradley 1987a). Having shown this process to be potentially very important and worthy of more thorough research we developed the OCTET simulation system—a three-dimensional, nonhydrostatic, and fully compressible atmospheric dynamics model with eight levels of detail for cloud microphysics and aerosol scavenging (Figure 1). Simulations with OCTET indicated that a substantial amount of the smoke from intense fires would be removed by cloud processes (Bradley, 1987b).

To improve our estimate of the fraction of smoke removal by precipitation and to more accurately represent the physics of the scavenging processes in OCTET we used results from a separate, detailed microphysical model of cloud droplet-aerosol interactions (Penner et al., 1991). Our results showed that at least one-third of the smoke emitted by large, intense fires could indeed be scavenged by precipitation and that the remaining smoke would be injected into the upper troposphere and stratosphere (Molenkamp and Bradley, 1991; Bradley and Molenkamp, 1991).

As part of the validation of OCTET's ability to simulate potential, nuclear-detonation-related fires, we simulated actual burns of diseased forests and, in cooperation with the Canadian Forestry Service, compared our model results with observational data. Figure 2 shows our simulation of the 1988 Battersby Township fire in Ontario, Canada. The sequence of turrets in this simulation agreed well with the observations of the actual fire; the rather unusual cloud structure was a result of interactions between the thermal forcing of the fire and the ambient winds.

The OCTET system was also used to investigate the operational implications of smoke in a post-nuclear-exchange environment (Bradley et al., 1990). Using a mesoscale model, we showed that large temperature contrasts will not occur at the continental boundaries in a post-nuclear-exchange environment because stratus clouds will form over both land and sea as the atmosphere cools (Molenkamp, 1989a,b). Previously, others had hypothesized that these large temperature contrasts would result in strong convection acting as a removal mechanism for large quantities of injected smoke.

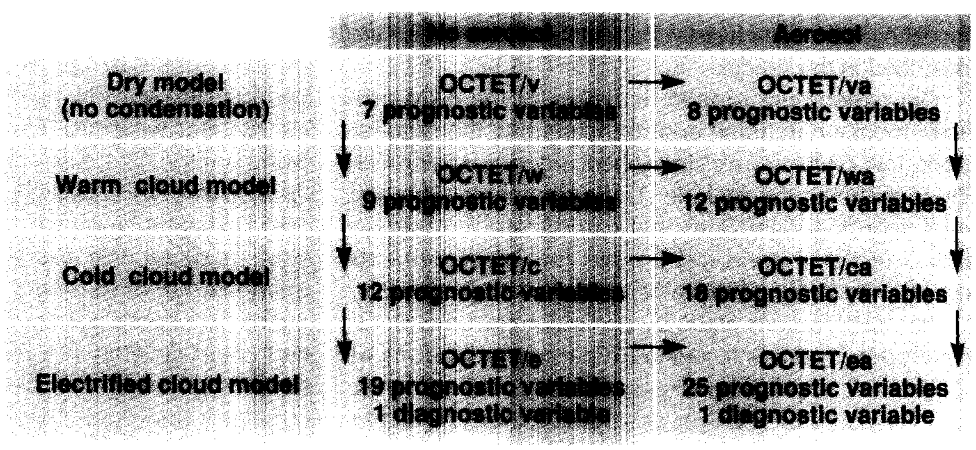

Figure 1. The hierarchical structure of the OCTET Plume, Storm, and Mesoscale Simulation System. The arrows indicate the path from least to most comprehensive of the eight models within the system. The dry model does not have any hydrometeors; the warm cloud model has only liquid hydrometeors; and the cold cloud model has both liquid and ice hydrometeors. The electrified cloud model, which is not yet implemented, would include both liquid and ice and would allow the hydrometeors to carry electric charges.

Clouds and Climate

Our cloud physics research focuses on the detailed aspects of local and regional cloud-climate interactions. Because clouds have a major impact on the Earth's climate, they must be adequately represented in numerical models of global circulation. In general, cloud feedback on larger-scale systems is manifest in two ways: (1) thermodynamic effects, such as latent heating and removal of moisture; and (2) radiative effects, resulting from scattering and absorption of radiant energy. We are currently using a cloud model to study how climate is affected by the interaction of clouds with solar and terrestrial radiation. This model's dynamic framework is similar to OCTET's, but it includes representations of radiation

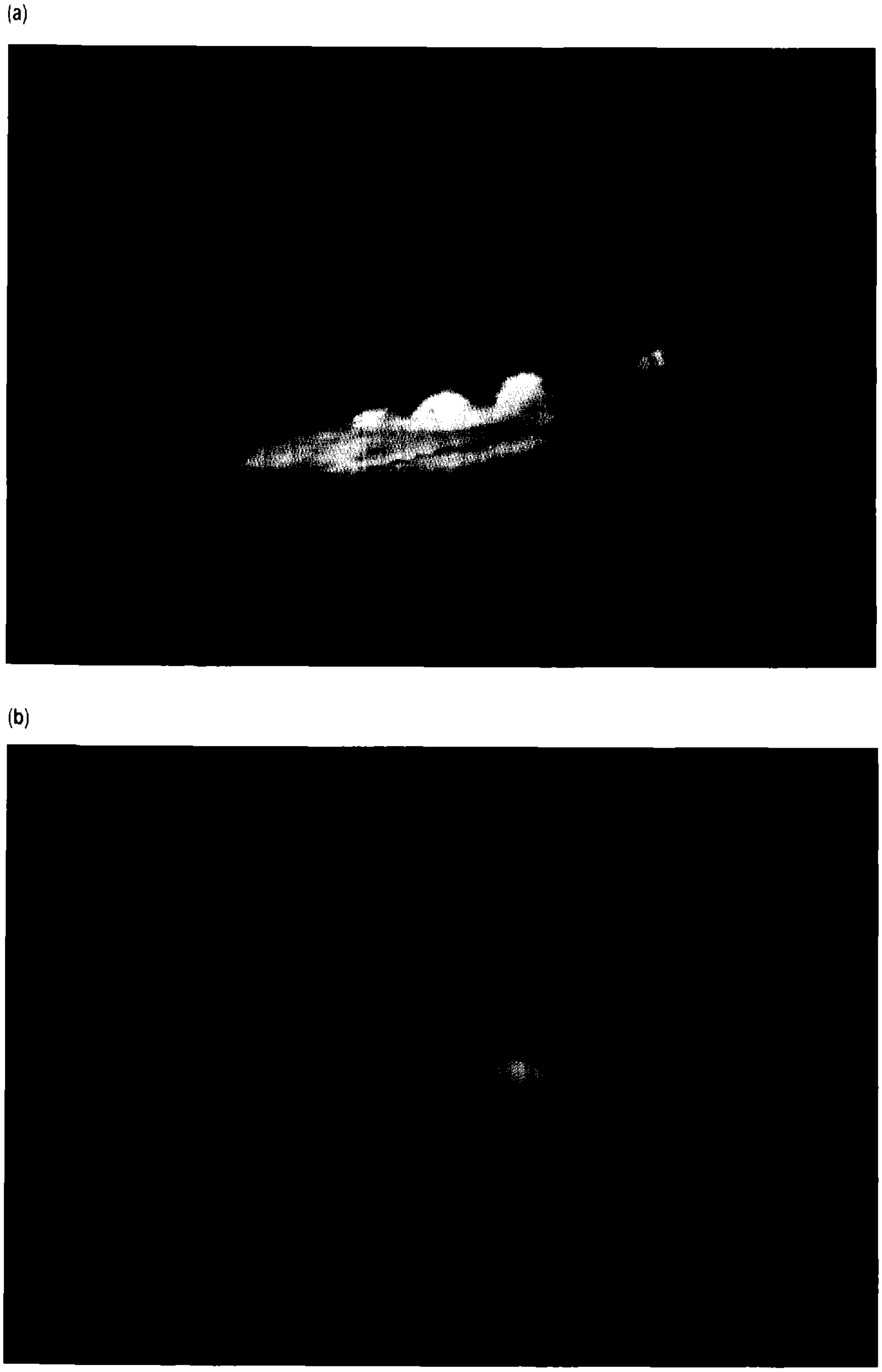

Figure 2. A simulation of the smoke and hydrometeor distribution for the 1988 Battersby Township fire in Ontario, Canada. The domain is 36 km long, 18 km wide, and 12 km tall and is viewed from the southwest. The colors in the simulation represent **(a)** smoke (gray), cloud water (white), and ice crystals (yellow); and in **(b)** smoke (gray), snow (white), graupel (red), fire (orange), and rain (blue).

and surface boundary-layer processes, and it does not include the aerosol scavenging module.

Using this cloud model, we investigated the consequences of including the ice phase with its enhanced latent heat release and radiative properties. We found that this had only a small effect on the large-scale dynamics and thermodynamics, but it had a significant effect on the large-scale radiative heating and cooling (Chin et al., 1991). Figure 3 shows that the infrared (long-wave) heating is nearly the same for the all-liquid and all-ice clouds except for the height differences. Moreover, the solar (short-wave) heating of optically thick, all-liquid anvil clouds results in vertical growth and, thus, even greater optical depths (i.e., they tend to preserve themselves); whereas solar heating of optically thin, all-ice anvil clouds tends to dissipate the anvil and, thus, decreases optical depths and cloud lifetimes.

Experiment Support

The majority of work in the experiment support area is funded by the DOE Atmospheric Radiation Measurement (ARM) program and is focused on developing and implementing algorithms that can transform observational data from field instruments into measurements used for modeling. We provide the leadership for this effort and also provide interfaces to Science Team members working in the Single-Column Model, Hierarchical Diagnosis Model, and Data Assimilation Model areas. As members of the ARM Experiment Support Team, our group has had the opportunity to work with numerous scientists from universities, federal laboratories, and the private sector.

One of our primary roles is to provide an interface between the modelers and theoreticians and the sources of applicable data. A critical part of the interface for providing requested measurements to modelers is the procedure used for producing the measurement. Often the requested measurement involves a variable that is not directly observed, but instead must be derived from other observations and, perhaps, other types of measurements as well (Figure 4). At the heart of the procedure is the algorithm that transforms the input data into the requested measurement. Selecting specific algorithms involves identifying candidate algorithms and deciding whether to develop them ourselves or to acquire them outside ARM. During implementation, algorithms are tested and documented, and their versions are controlled using configuration management to ensure repeatability of measurements. As part of our experiment support effort, we assist the ARM Science Team members in developing their experiment designs; we later translate these designs into experiment operational plans for implementation at the ARM experiment center.

DOE ARM Program

The objective of the DOE ARM program is to characterize radiative processes in the atmosphere with improved resolution and accuracy in order to develop more accurate general circulation models (GCMs) for studying climate change (DOE, 1990). Because clouds play an important role in radiative forcing and feedback mechanisms, a key factor in improving this characterization is the effective treatment of cloud formations and properties in GCMs. There is a natural synergism between ARM's interest in clouds and the cloud modeling performed in our group.

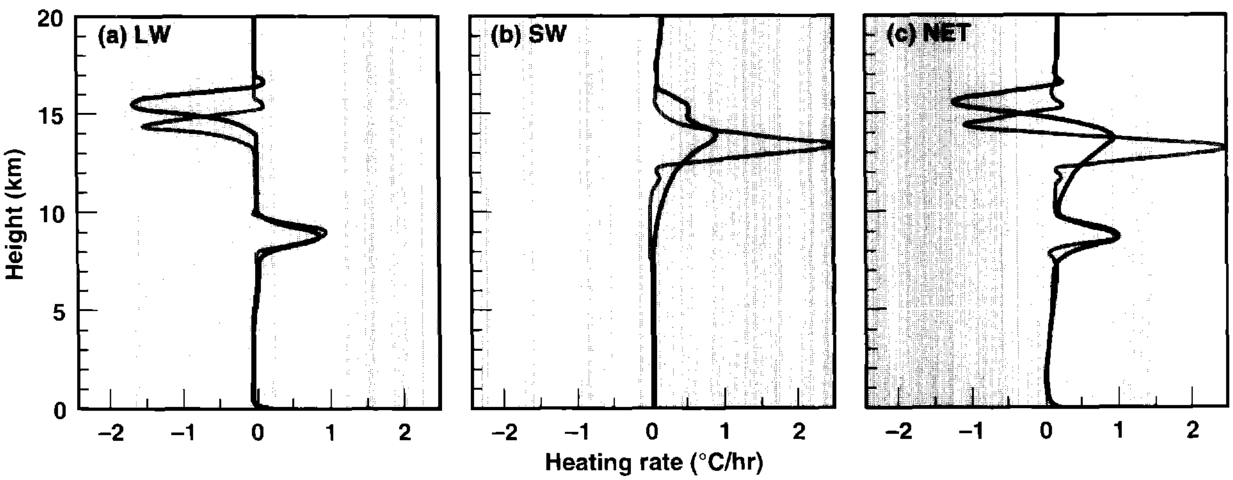

Figure 3. Radiative heating rates of all-liquid (blue line) and all-ice (black line) anvils: **(a)** long-wave radiation at 0° zenith angle; **(b)** short-wave radiation at 0° zenith angle; and **(c)** the sum of (a) and (b).

Atmospheric processes that affect radiative transfer are being investigated over a wide range of temporal and spatial scales. These various approaches require that ARM Science Team members use a multitude of diverse data sets. The data are used for model input, comparison with model results, and diagnosis of model performance. We call such data sets *measurements*. The data sets that come from ARM instruments are called *observations* and are used with data sets from outside the ARM program for producing measurements.

ARM's approach to reaching its goals is to provide a testbed for evaluating key components of GCMs and related models. The experimental apparatus that ARM uses is called the Clouds and Radiation Testbed (CART), which consists of observation sites, an experiment center, and a shared data environment for testing models.

The measurement requirements of the ARM scientists are being addressed by development of a General Measurement Strategy (GMS) for each of four categories: instantaneous radiative flux, single-column models, data assimilation, and hierarchical diagnosis. We are responsible for all GMS categories, except the first. We have documented the measurements required to support ARM experiments, specifying measurement attribute values (i.e., accuracy, and spatial and temporal resolution) and the procedures (including algorithms) used to produce measurements from CART observations and data obtained from outside CART.

The instantaneous radiative flux (IRF) GMS quantifies atmospheric-state variables relevant to radiative transfer in narrow vertical columns (straws), cones, and hemispheres above the CART site (Figure 5a). Observations are required for an almost instantaneous characterization of the atmosphere under clear and cloudy conditions, and they must be concurrent with observations of the instantaneous radiative field. Radiative measurements may be spectrally resolved or integrated over all wavelengths and directionally resolved or integrated over all solid angles.

The single-column model (SCM) GMS provides information for a column of large cells about the size of the CART site (Figure 5b). Hence, the areal coverage of the SCM measurements is typically larger than for the IRF GMS, and the volume or area represented is also much larger. SCMs are computationally efficient tools for developing and testing parameterizations of atmospheric processes that occur on scales too small to be resolved by GCMs. The SCM is basically one column of a GCM that can be run as a separate entity. The information normally provided to the GCM column by adjacent cells must be provided in the SCM by boundary conditions that force the SCM. The required measurements include surface-boundary conditions averaged over the CART site, as well as dynamic, thermodynamic, precipitation, radiative, and macroscopic cloud properties provided as surface averages or vertical profiles of horizontally-volume-averaged (slab) values.

The data assimilation (DA) GMS supports models that produce dynamically consistent data sets from CART observations and includes measurements similar to the SCM GMS. In the case of single-column DA, the measurements are usually identical. Four-dimensional data assimilation (FDDA), which uses a mesoscale model as its base, requires measurements at finer resolution in space and time (Figure 5c). These measurements are in two- and three-dimensional grids and are interpolated from CART observations and measurements as well as from observations outside of CART. The atmospheric fields produced by DA are used to evaluate how well SCM parameterizations represent atmospheric processes at spatial and temporal scales too small to be resolved by the SCM.

Finally, the hierarchial diagnosis (HD) GMS provides measurements at an even finer resolution than the DA

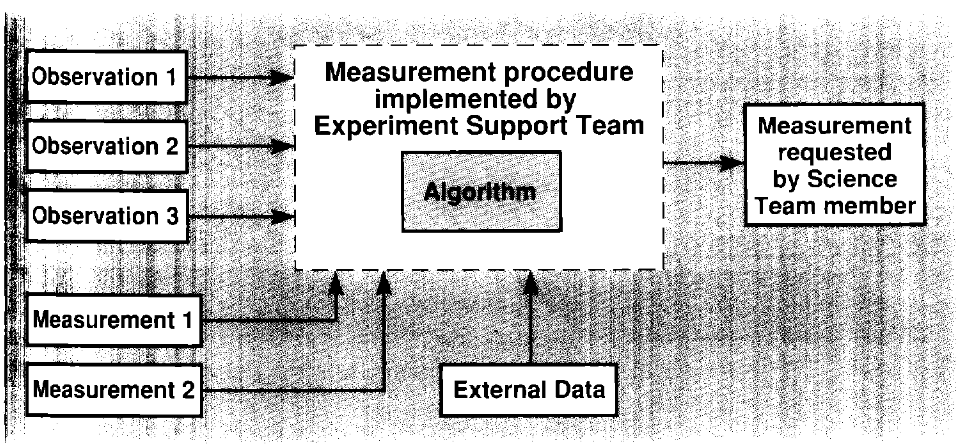

Figure 4. The measurement requested by a Science Team member often involves a variable that is not directly observed. An algorithm is used to derive these variables from other observations, and in some cases from other types of measurements.

and includes microphysical and macrophysical cloud properties (Figure 5d). The microphysical cloud measurements may often require in situ observations taken from airborne platforms. Basically, the HD GMS involves the use of fine-resolution models and measurements to diagnose the performance of coarser resolution models and to develop improved parameterizations (representations) of fine-scale processes for coarse-scale GCMs. In the GCMs, limitations in computational resources often constrain not only the grid resolution, but also the "resolution" of the physics. Models exercised in the HD GMS use more complete or elaborate descriptions of the relevant physics. For example, a detailed cloud model that includes microphysical parameterizations could be used to diagnose the performance of a GCM cloud parameterization that uses only relative humidity and vertical velocity to infer the formation of clouds.

Testbed for GCM Parameterizations

For the ARM program, a general issue of interest is the parameterization of the net effect of smaller-scale physical processes acting within a single GCM cell. To this end, we are developing an SCM option for the widely used UCLA GCM; it will allow the user to design and simulate ARM observation periods directly with the components of a state-of-the-art GCM. The UCLA model's

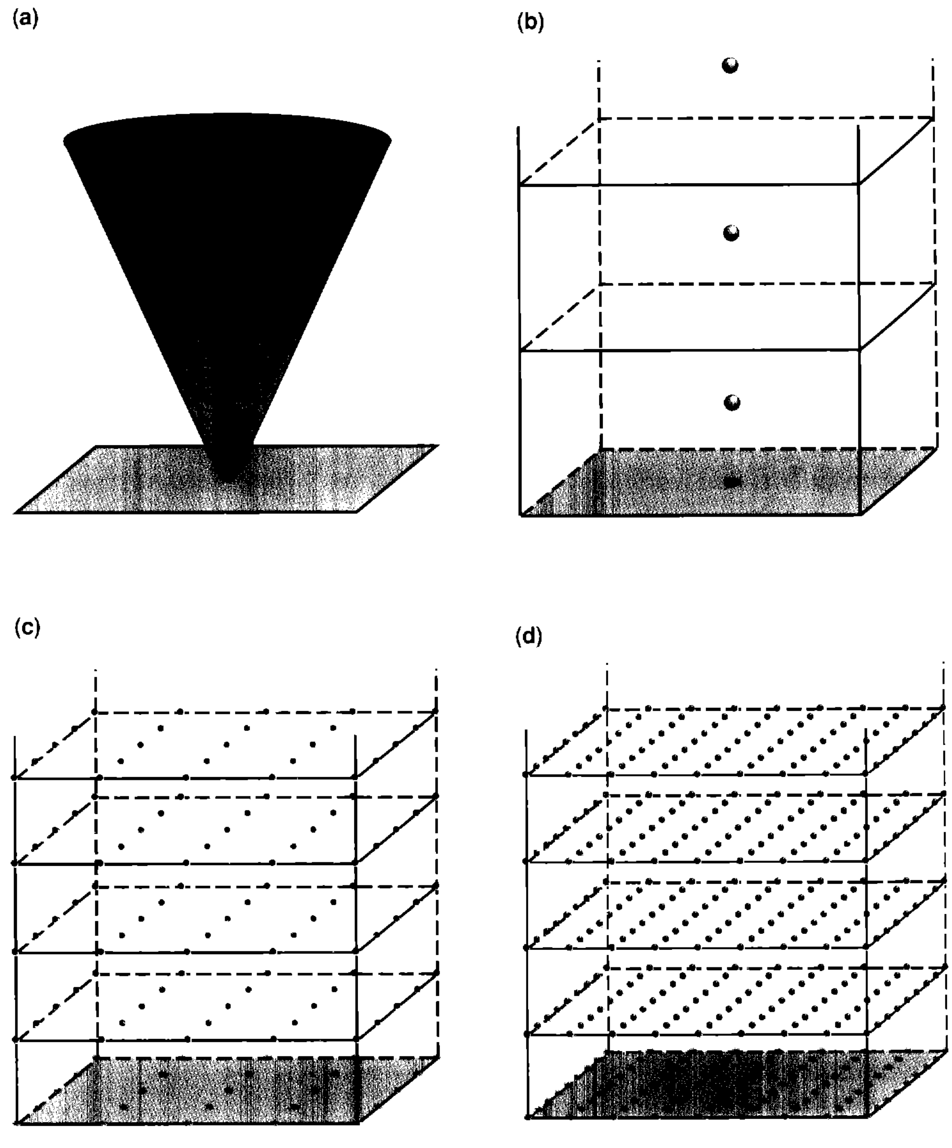

Figure 5. Four categories of General Measurement Strategies (GMSs) are used to document the measurements at the Clouds and Radiation Testbed (CART) site. **(a)** The instantaneous radiative flux GMS quantifies atmospheric-state variables relevant to radiative transfer in narrow vertical columns, cones, and hemispheres above the CART site (blue region); **(b)** the single-column model GMS provides data for a column of large cells about the size of the CART site; **(c)** the four-dimensional data assimilation GMS, which uses a mesoscale model as its base, provides measurements at a finer resolution in space and time; **(d)** the hierarchical diagnosis GMS, which includes both microphysical and macrophysical cloud properties, provides measurements at an even finer resolution than the data assimilation GMS.

modifications will include updating the software coding to provide a more modular framework that will facilitate using this model as a testbed for evaluating parameterizations of physical processes. Measurements from observations at the CART site can be used directly in place of model components to more stringently constrain the remaining model components. Thus, the SCM is intended to function as the climatological limit of a high resolution treatment of the CART site.

Future Plans

The impact of cloud processes goes far beyond the local effects of a rain shower or a severe storm complex. Society is becoming increasingly aware that current activities and future technological advances have the potential to adversely alter not only the local environment, but also the global climate. Greenhouse warming, depletion of the ozone layer, and other anthropogenic, global-scale atmospheric problems all involve cloud processes. To meet the challenge of these problems, we will be further extending our cloud modeling capabilities, conducting relevant research, and encouraging development of the next generation of cloud scientists.

With the establishment of the first CART site in the Southern Great Plains area, the experiment support activity will move from a planning and preparation phase into an implementation and evaluation phase. During this transition, we will facilitate the near real-time interaction between modelers and ARM data. The second CART site to be established will be located in the western tropical Pacific area. The remoteness and the size (about 1000 × 7000 km) of this site will pose particular problems that will require creative solutions to support the proposed experiments.

Group Members

The work described in this article was performed by, or under the auspices of, the Cloud Modeling and Experiment Support Group. Scientists include Marvin H. Dickerson (Group Leader), James R. Albritton, William J. Bosl, Michael M. Bradley, Richard T. Cederwall, Hung-Neng (Steve) Chin, John M. Leone, and Charles R. Molenkamp.

We are participating with a number of researchers from other laboratories, universities, and institutes whose contributions may not be fully reported here. Appendix B provides a brief summary of these interactions.

Sponsoring Organization

This work has been supported by the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division through Battelle Pacific Northwest Laboratory and Los Alamos National Laboratory.

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Tropospheric Chemistry and Climate Change

Joyce E. Penner, Group Leader

Anthropogenic sources of trace species and aerosols are changing the composition of the troposphere. The Atmospheric Microphysics and Chemistry Group studies the biogeochemical cycles of these species to determine their effects on atmospheric chemistry and climate.

The Atmospheric Microphysics and Chemistry Group conducts research to improve the understanding of the physical, radiative, and chemical interactions of species injected into the lower atmosphere. These species, which are generally short-lived and photochemically active, impact the boundary layer and troposphere on regional-to-global scales. We are building the capability to predict the global distributions of these species in the troposphere and to model their impacts on atmospheric chemistry, clouds, and climate.

In 1987, our group was formed to build on the modeling expertise developed as a result of the Laboratory's effort to evaluate the global effects of nuclear war. Our earlier efforts have included the development of a three-dimensional aerosol model [GRANTOUR (Walton et al., 1988)] that can run independently or interactively with a climate model; process models that can provide a detailed microphysical description of the interactions of aerosols and cloud drops; and a three-dimensional cloud model that can provide a bulk microphysical description of aerosols and cloud processes.

We are now developing global models of the distribution of tropospheric aerosols and their coupling to atmospheric chemistry. We are also performing application studies to verify if specified biogeochemical and anthropogenic sources and sinks of trace species are consistent with their measured atmospheric concentrations and our knowledge of atmospheric transport and transformation processes. These efforts involve estimating global trace-gas source profiles and linking these estimates to atmospheric chemistry models. To estimate the magnitude and pattern of the radiative forcing from increased anthropogenic trace gas and aerosol sources, we are linking our chemical and aerosol models to atmospheric climate models. We are also developing a method to incorporate in climate models the effects of increases in anthropogenic aerosols on cloud droplet concentrations and cloud albedo.

Tropospheric Ozone

Tropospheric ozone affects climate in two ways. First, it acts as a greenhouse gas. If concentrations of ozone increase (or decrease) in the troposphere, particularly at levels near the tropopause, the climate may warm (or cool). Second, photolysis of ozone produces an excited oxygen atom. This atom reacts with water vapor to produce hydroxyl radicals (OH), which are important chemical scavengers. If the concentration of ozone increases in the troposphere, the concentration of OH may also increase; subsequently, the abundances of a variety of different trace species that are removed by reaction with OH may decrease. Methane is one example of an important greenhouse gas whose lifetime and abundance is determined by its reaction with hydroxyl radicals.

Recent studies have determined that the concentration of ozone in the lower troposphere has increased at a rate of about 1% yr^{-1}, while the concentration of ozone in the lower stratosphere has decreased. Predicting the change in the upper troposphere is difficult because it depends on the relative importance of one of two pathways: (1) transport from the stratosphere where ozone is being destroyed, and (2) in situ photochemical production and transport from the ozone-producing regions in the lower troposphere. We know that both in the lower troposphere and over continents the potential for photochemical reactions to form ozone has been significantly increased by emissions of reactive nitrogen oxides (NO_x), nonmethane hydrocarbons (NMHCs), carbon monoxide (CO), and methane (CH_4); however, a number of complex interactions must be considered to accurately predict the global extent of the ozone increase. This presents a great challenge to the atmospheric modeling community; our goal is to meet this challenge by systematically incorporating more complete representations of ozone chemistry and dynamics into our global model.

Ozone is photochemically produced when nitrogen oxides react in the presence of CO, CH_4, NMHCs, and sunlight. There are several hydrocarbons that, together with CO, ultimately lead to ozone production. They may be divided into three categories. The first category consists of the most abundant and chemically simple hydrocarbon CH_4, which has many natural and anthropogenic sources. The second category consists of biogenic hydrocarbons such as isoprene and terpenes, which are emitted by vegetation. These hydrocarbons are highly reactive and may be responsible for a significant portion of the ozone formed near non-urban regions. The third category of compounds contains many of the hydrocarbons emitted by industrial and commercial processes, such as the alkanes, alkenes, aromatics, and aldehydes. Many of these are quite reactive and contribute to ozone formation on a local-to-regional scale. Some of the ozone produced regionally is also exported to remote continental and oceanic areas. In addition, many of the alkanes emitted from human activities, especially the lighter alkanes, have long chemical lifetimes, can be transported over long distances, and can contribute to in situ ozone production over remote areas.

Over the last two years, we continued to develop our global model of tropospheric ozone chemistry. Initial results from this modeling effort indicate that the anthropogenic sources of nitrogen oxides may have increased lower tropospheric ozone concentrations substantially in regions where fossil fuel emissions of NO_x dominate over other sources, such as in the eastern U.S. and Europe. Figure 1 shows a simulation for July in which CO and CH_4 concentrations have been prescribed and the effects of NMHC emissions are not included. These results show that ozone concentrations over industrialized regions appear to be about twice as high as ozone concentrations in remote ocean regions. We are now working to improve our model so that we can incorporate additional chemical interactions and test more efficient numerical solution techniques. Three different numerical schemes for atmospheric chemistry have been installed in the GRANTOUR tropospheric ozone model in an effort to find the most efficient and accurate solution technique for the mathematically stiff system of equations. We are now conducting global simulations using a new version of our original predictor/corrector solution technique and are planning to use the GRANTOUR tropospheric ozone model to investigate the role of anthropogenic sources of NO_x and the natural biogenic sources of hydrocarbons on the tropospheric ozone budget.

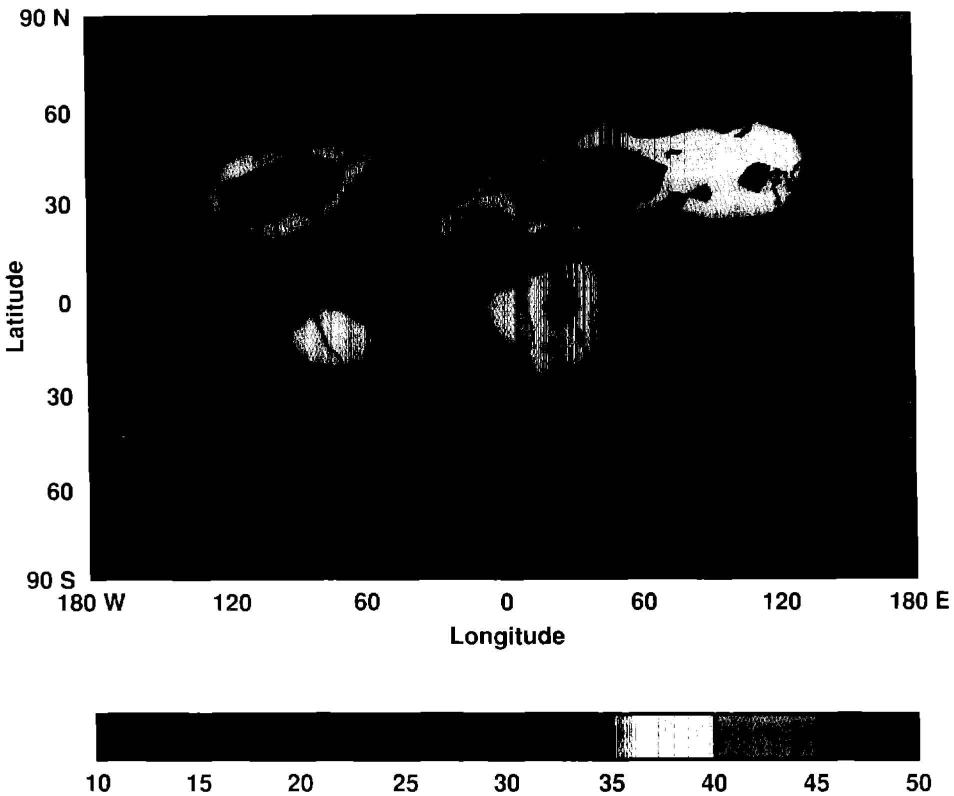

Figure 1 Predicted ozone concentrations at 926 mbar (700 m) above surface for July assuming all sources of reactive nitrogen oxides are included in the model. Contour units are in parts per billion by volume. Ozone concentrations are about twice as high over industrialized regions as over oceanic regions due to the anthropogenic emissions of nitrogen oxides.

Nitrogen Oxide Emissions

The main sources of NO_x ($NO_x = NO + NO_2$) in the troposphere are fossil-fuel combustion (Dignon, 1992), biomass burning, lightning, soil-microbial activity, and transport from the stratosphere. NO_x affects the climate through its role in the chemistry of tropospheric ozone and OH. In regions of high NO_x concentrations, photochemical sequences tend to favor ozone production; in regions of low NO_x concentrations, the sequences lead to net ozone destruction. Also, the OH concentration depends on the concentration of NO_x. At background levels of CO and CH_4 the OH concentration should peak at nitric oxide (NO) concentrations between 200 and 500 ppt, although it will decrease with either higher or lower NO concentrations.

The emissions of NO_x from fossil fuel combustion and biomass burning are increasing. Recent simulations using our three-dimensional model show that these anthropogenic sources of NO_x may have contributed to increases in NO_x concentration over vast portions of the marine atmosphere (Penner et al., 1991), which would be expected to lead to an increase in ozone concentration in these areas. To accurately predict the effects of increases in anthropogenic emissions of NO_x, we must also consider the natural sources of NO_x. The following two sections describe studies of both anthropogenic and natural sources of NO_x.

Sources of NO_x from Biomass Burning

We have developed a gridded global inventory of the emissions of NO_x from biomass burning using estimates of the amount of biomass burned in each region together with estimates of the dominant type of vegetation and its nitrogen content (Dignon and Penner, 1991). An empirical relationship between the nitrogen content of the biomass fuel and NO_x emissions during burning was then used to obtain a gridded global inventory. The emissions of NO_x per-unit-area from biomass burning around the globe are shown in Figure 2. Heavy burning for deforestation is responsible for most of the emissions in Brazil, and heavy burning to clear land for shifting agriculture is responsible for most of the emissions in Africa. These results indicate that the total emission rate is nearly twice as high as previous inventories (~13 Tg N yr^{-1}), highlighting the importance of this source in perturbing the natural cycle of nitrogen oxides. We are evaluating the effects of these additional NO_x emissions on tropospheric ozone concentrations.

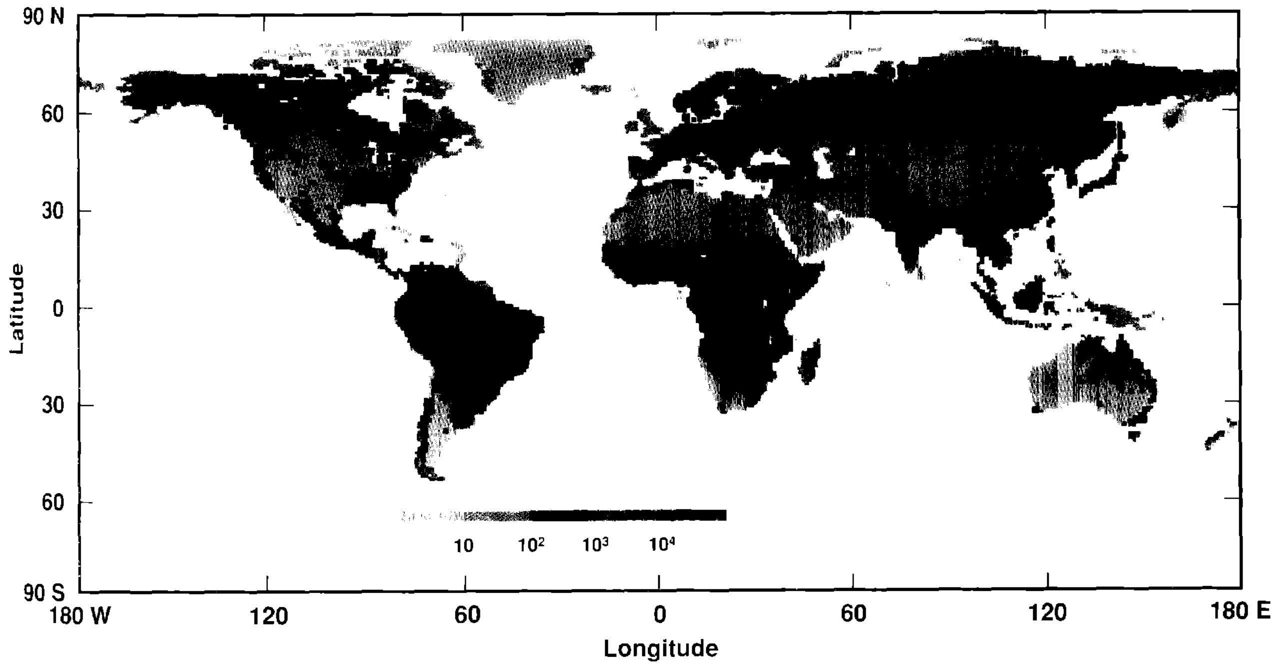

Figure 2. Global emissions of NO_x (g N m^{-2}) from biomass burning. Emissions are high over Brazil due to contributions from deforestation and high over Africa due to fires associated with shifting agriculture.

Natural Sources of NO_x

We have also developed a monthly inventory of NO_x emissions from microbial activity in soils of natural ecosystems (unperturbed by nitrogen fertilization) and have evaluated their effects using our three-dimensional nitrogen-cycle model (Dignon et al., 1992). For this inventory, we used gridded data on the moisture, temperature, and vegetative cover of the soil, along with empirical relationships, to estimate the amount of NO_x emissions. Emissions from soils, which are estimated to total ~ 5 Tg N yr^{-1}, are shown in Figure 3 for January and July. These maps show that natural soil emissions are small in desert regions and colder climates, but that extensive natural soil emissions occur over North America and Asia in the summer, indicating the strong temperature dependence of the soil processes.

In another study, our three-dimensional model was used to determine the bounds on the possible magnitude of the lightning source of NO_x (Atherton et al., 1991). We found that previous estimates of the magnitude of this source (which ranged as high as 100 Tg N yr^{-1}) were not compatible with measured atmospheric nitrate concentrations and deposition amounts; the model results were most compatible with a source magnitude of 20 Tg N yr^{-1}. This is the value we now use in our global simulations of tropospheric ozone.

Methane and Hydroxyl Concentrations

Recent increases in the emissions of CH_4 and CO may be contributing to the concentration of ozone in the troposphere. Accurate predictions of future concentrations of CH_4 depend on an accurate treatment of the chemical interactions that determine the OH abundance, because reaction with OH is the major removal mechanism for CH_4. This has been studied using one- and two-dimensional models that have been tuned to represent different "chemically coherent" regions within the troposphere.

We used a preliminary simulation of ozone to predict the global three-dimensional field of OH concentrations. This field was used with a specified CH_4 concentration field to calculate the photochemical destruction of CH_4 in the atmosphere. The calculated loss rate was in the middle range of most estimates of the total source strength of CH_4. Our model can also be used to examine the role of CH_4 in greenhouse warming of the climate for both pre-industrial and future atmospheres.

Terrestrial Biogeochemical Cycling

We are developing a model called TERRA to study the productivity of the terrestrial ecosystem and the biogeochemical cycling of the important nutrient elements, initially carbon and nitrogen. The TERRA model was initiated to estimate dynamic fluxes of carbon dioxide (CO_2), CH_4, and other trace gases between the Earth's surface and the atmosphere. Productivity and cycling are represented by a set of coupled, nonlinear ordinary differential equations that calculate water fluxes of evaporation, transpiration, and runoff; carbon fluxes of gross primary productivity, litterfall, and respiration; and nitrogen fluxes of vegetation uptake, litterfall, mineralization, and system loss. The state variables are soil water content, carbon in live vegetation, carbon in soil, nitrogen in live vegetation, organic nitrogen in soil and litter, and available inorganic nitrogen aggregating nitrites, nitrates, and ammonia. TERRA is designed with 17 ecosystem types and requires the following input data: monthly averages of atmospheric CO_2, mean daily maximum temperature, mean daily minimum temperature, monthly precipitation, relative humidity or dewpoint temperature, and cloudiness or total radiation. The CO_2 level is important because vegetation productivity is a function of CO_2. Increased CO_2 has a fertilization effect on trees and temperate zone plants and increases the water-use-efficiency of virtually all species. We have implemented a calibration version of TERRA that is now being tested. The increase in water-use-efficiency at increased CO_2 levels is still being developed. Next, a global version will be implemented and linked to the atmospheric chemistry model to study the exchanges of CO_2 and other trace gases between the Earth's surface and the atmosphere.

Aerosol Emissions and Their Climate Effect

Recent studies have estimated that anthropogenic emissions of sulfur dioxide lead to a source strength for anthropogenic sulfate ($SO_4^=$) aerosols, totaling about 120 Tg $SO_4^=$ yr^{-1}. The resulting aerosol burden could exert a cooling influence of up to –2 Wm^2 on a global average basis (Charlson et al., 1992). Half of the climate forcing is estimated to result from the direct reflection of sunlight by aerosol particles and half from the indirect effect of aerosol particles on cloud droplet concentration and cloud reflectivity (albedo). We are developing the capability to treat the

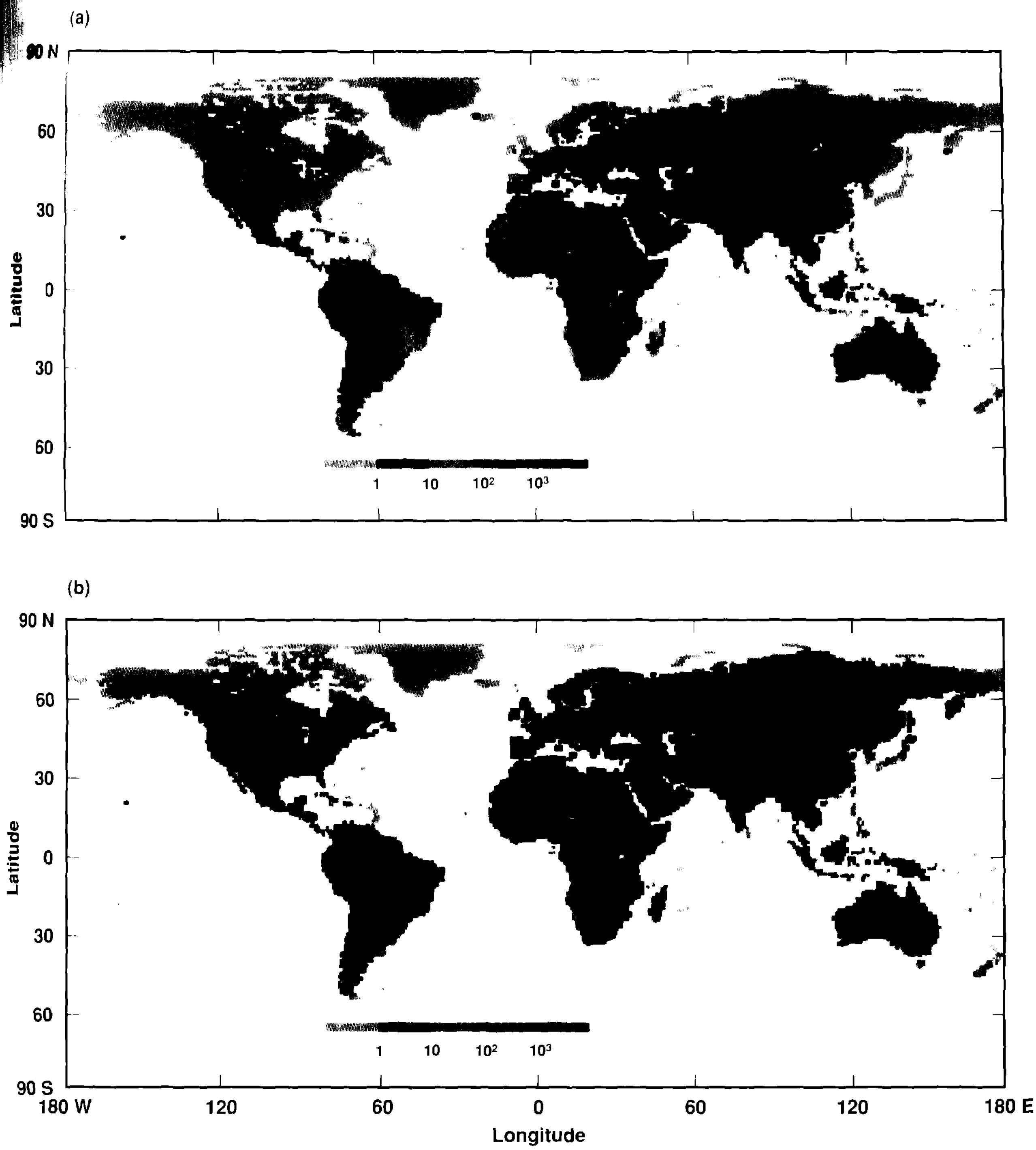

Figure 3. Global emissions of NO_x (mg N m^{-2} yr) from soils for (a) January and (b) July. Seasonal variations in the biological activity can be seen by comparing (a) and (b), particularly in northern mid-latitudes.

direct and indirect effects of sulfur aerosols in a climate model. Our calculations indicate a forcing of about -1 Wm^{-2} from the direct reflection of sunlight by anthropogenic sulfate aerosols (Chuang and Penner, 1992). We have also estimated the indirect forcing from sulfate aerosols, but the calculation of this forcing is highly simplified and the magnitude of the forcing is quite uncertain (see following section). Figure 4 shows the predicted distribution of sulfate aerosol mass from fossil fuel combustion and other anthropogenic sources of sulfur in our model. The model calculations indicate that sulfate from anthropogenic sources is spread throughout the Northern Hemisphere.

Smoke aerosols from biomass burning could have a similar cooling effect on the climate. We used estimates of the amount of biomass burning in the tropics for land-clearing purposes with measured emission factors to estimate a total aerosol source strength of 80 Tg yr^{-1}. Additional sources of aerosols from the burning of wood, agricultural refuse, and charcoal raise the estimated total to 114 Tg yr^{-1}. We found that these smoke aerosols mainly scatter solar radiation and (like sulfate) reflect about 1 Wm^{-2} of solar radiation (Penner et al., 1992a). The smoke aerosols also act as good cloud condensation nuclei and so may be expected to change cloud albedo. We estimated a total cooling force of -1.8 Wm^{-2} from aerosols produced by the burning of biomass. Together with the above estimate of the climate forcing by sulfate aerosols, the total forcing from anthropogenic aerosols may be on the order of -4 Wm^{-2}.

Because the estimated forcing from greenhouse gases is about 2.5 Wm^{-2} and because global temperatures appear to be increasing (consistent with a net positive forcing), it appears that climate forcing by anthropogenic aerosols may now be overestimated. One possible factor contributing to this overestimation may be the effects of aerosols on cloud albedos. A second possible factor may be the effects of emissions of soot (or black carbon), which could contribute to a positive forcing by increasing aerosol absorption of solar radiation. We are examining these possibilities in two separate research efforts.

Radiative Forcing by Sulfate Aerosols: Effects on Cloud Albedos

Calculating the effects of sulfur aerosols on cloud albedos requires knowledge of (1) aerosol particle size distribution, (2) updraft velocities, and (3) sub-grid scale variations in velocities. We are developing a

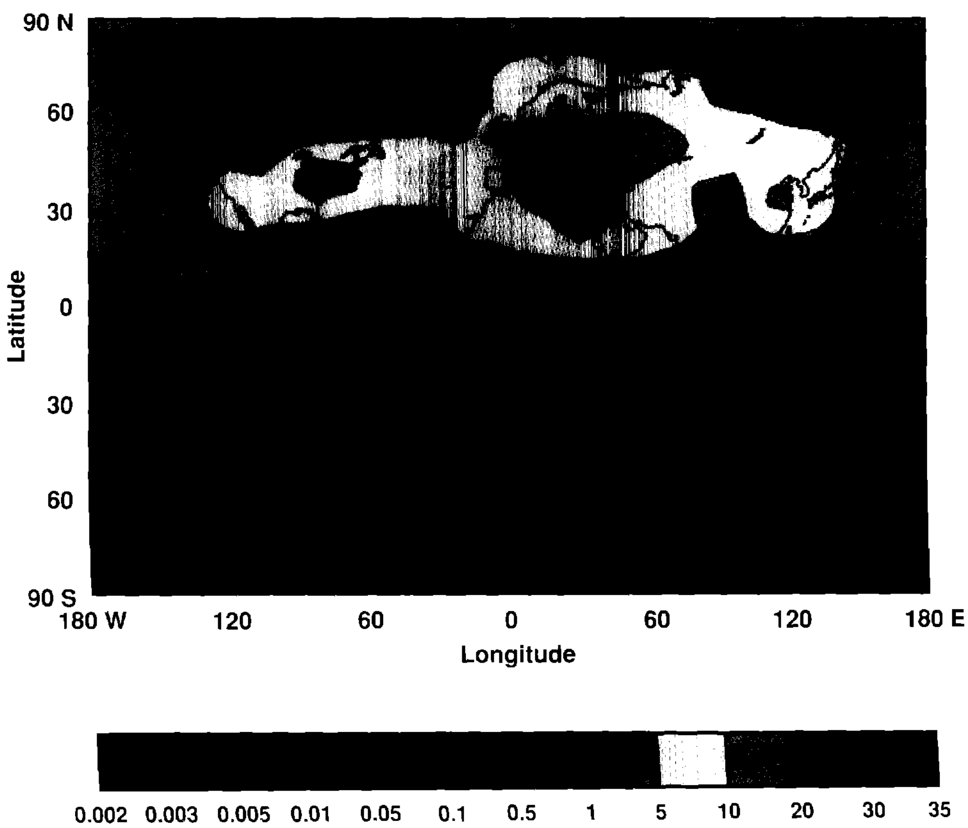

Figure 4. Integrated column loading of sulfate aerosol mass (mg $SO_4^{=}$ m^{-2}) from anthropogenic sources of sulfur. These aerosols reflect solar radiation, thereby cooling the climate. Sulfate concentrations are highest over and downwind of industrialized nations.

three-dimensional model of the sulfur cycle that accounts for all of these processes. We initiated efforts to describe the sulfur cycle with a fairly simple photochemical model (Erickson et al., 1991) that was then expanded to treat a larger set of chemical reactions. A comparison of the results to observational data and to the results from other three-dimensional models showed that the model can adequately describe the distribution of sulfate mass in the atmosphere.

We are now working to incorporate a method for predicting the size distribution of the sulfate aerosol particles. This requires adding a description in the model that accounts for the gas-to-particle conversion of sulfur dioxide (SO_2) to sulfate aerosol. Sulfuric acid vapor is formed in the atmosphere from the gas phase oxidation of SO_2. The H_2SO_4 vapor formed by this gas phase production mechanism is not stable. It may either nucleate to form a new, small aerosol particle or it may condense on a preexisting particle. This latter process will form a larger, more sulfate-rich particle, but no new particles. Sulfur dioxide may also be converted to sulfate aerosol in cloud droplets via aqueous reactions with hydrogen peroxide or ozone. All these effects must be properly treated to predict the sulfate aerosol size distribution.

The sulfate aerosol size distribution is needed to calculate the effects of sulfate aerosols on cloud albedo. Once the sulfate aerosol size distribution is known, the effects of aerosols on cloud droplet size distributions can be predicted using the experience gained in studies of biomass burning plumes (Chuang et al., 1992). Initially, we used a parameterization that assumed a prescribed aerosol size distribution in order to evaluate the indirect effects of sulfur aerosols on climate (Chuang and Penner, 1992). The predicted climate forcing was close to $-3\ Wm^{-2}$. This value is very large relative to the estimated warming by greenhouse gases and suggests the need to carefully reexamine the representation included in the model.

Black Carbon Emissions and Their Climate Effect

The emissions of soot or black carbon (BC) are important because BC is the principal light-absorbing component of aerosols and may thereby act to absorb radiation, counteracting to some extent the direct reflection of sunlight by sulfur aerosols. We have used the measured ratio of BC to SO_2 in urban areas with emission inventories of SO_2 to develop a global emission inventory for BC. We developed a second estimate of the BC emission inventory by combining known fuel use and production statistics with estimated emission factors for diesel fuel use, coal use in the domestic and commercial sectors, and wood burning. The two inventories totaled 24 Tg C yr^{-1} and about 13 Tg C yr^{-1}, respectively (Penner et al., 1992b). The inventory based on the ratio method was used in our three-dimensional aerosol model, and the predicted BC concentrations from this model were compared to available measurements. The results of this comparison support the estimated magnitude of the BC emission inventory derived from the ratio method to within a factor of 2. Figure 5 shows the estimated soot aerosol mass from the larger of the two inventories. We estimate that BC emissions may decrease the cooling effect of sulfate aerosols by 20 to 40% in the Northern Hemisphere (Penner and Novakov, 1992). We plan to investigate the effects of BC emissions in our linked aerosol-chemistry-climate model.

Future Plans

The goal of the Atmospheric Microphysics and Chemistry Group is to define and test whether or not specified biogeochemical and anthropogenic sources and sinks of trace species are consistent with their measured concentrations and our knowledge of transport and transformation processes in the atmosphere. In this way, we hope to develop the capability to predict atmospheric chemistry and climate change. To accomplish this goal in its entirety requires the development of models that also treat the biogeochemical cycling of trace species in the ocean and the terrestrial biosphere because the sources and sinks from these components of the Earth's system are poorly defined and may change with time. We plan to link our atmospheric models to models that describe the chemistry of the ocean and the chemistry of ecosystems, thereby allowing a self-consistent understanding of whether our knowledge of the biogeochemical cycling of trace species is adequate. With these models, we hope to be able to predict the consequences of increased anthropogenic emissions in the future.

We will continue to develop our global model of tropospheric ozone chemistry by adding nonmethane hydrocarbon chemistry and an explicit prognostic treatment for carbon monoxide and methane. Our sulfur model will be linked to a climate model to evaluate the possible regional changes in climate expected from anthropogenic aerosol emissions.

We are also planning to link our three-dimensional chemistry model to wind and precipitation fields derived from observed data in order to simulate the expected concentrations of trace species for particular time periods. These simulations will be important in validation studies in which model results are compared with measured concentrations.

We are also planning to link our sulfur model to a climate model that treats the formation of clouds in a prognostic manner. This will allow us to more completely describe aqueous chemical interactions (e.g., the conversion of SO_2 to sulfate) and to evaluate the effects of anthropogenic aerosols on the colloidal stability of clouds and the resulting climate impact from alteration of cloud lifetimes. We expect to expand our treatment of aerosols to include the injection and transport of dust to ocean regions where the iron content of the dust may act as a nutrient for ocean productivity. Eventually all of the important aerosol components (i.e., sulfates, organics, nitrates, ammonium, dust, and sea salts) will be included.

With other groups in G-Division, we are exploring the development of a three-dimensional finite-difference model that will include a description of both tropospheric and stratospheric chemistry and will be suitable for extended simulations on massively parallel computers. This will allow more complete studies of atmospheric chemistry than were previously possible. We are also working to interface our model with developing versions of an integrated Earth System Model (see the "Modeling Global Climate Change" article later in this report) and to perform application studies that test the representations of processes coupling atmospheric chemistry to the biogeochemical cycles of the land and oceans.

Group Members

The work described in this article was performed by, or under the auspices of, the Atmospheric Microphysics and Chemistry Group. Scientists involved include Joyce E. Penner (Group Leader), Cynthia S. Atherton, Daniel J. Bergmann, Catherine C. Chuang, Jane E. Dignon, Hal E. Eddleman, Benjamin C. Graboske, John K. Hobson, James R. Kercher, Charles M. Molenkamp, Charles J. O'Connor, Gregory H. Rau, and John J. Walton.

We are participating with a number of researchers from other laboratories, universities, and institutes whose contributions may not be fully reported here. Appendix B provides a brief summary of these interactions.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division; the LLNL Laboratory Directed Research and Development program; Battelle Pacific Northwest Laboratory; the National Aeronautics and Space Administration; and the Environmental Protection Agency.

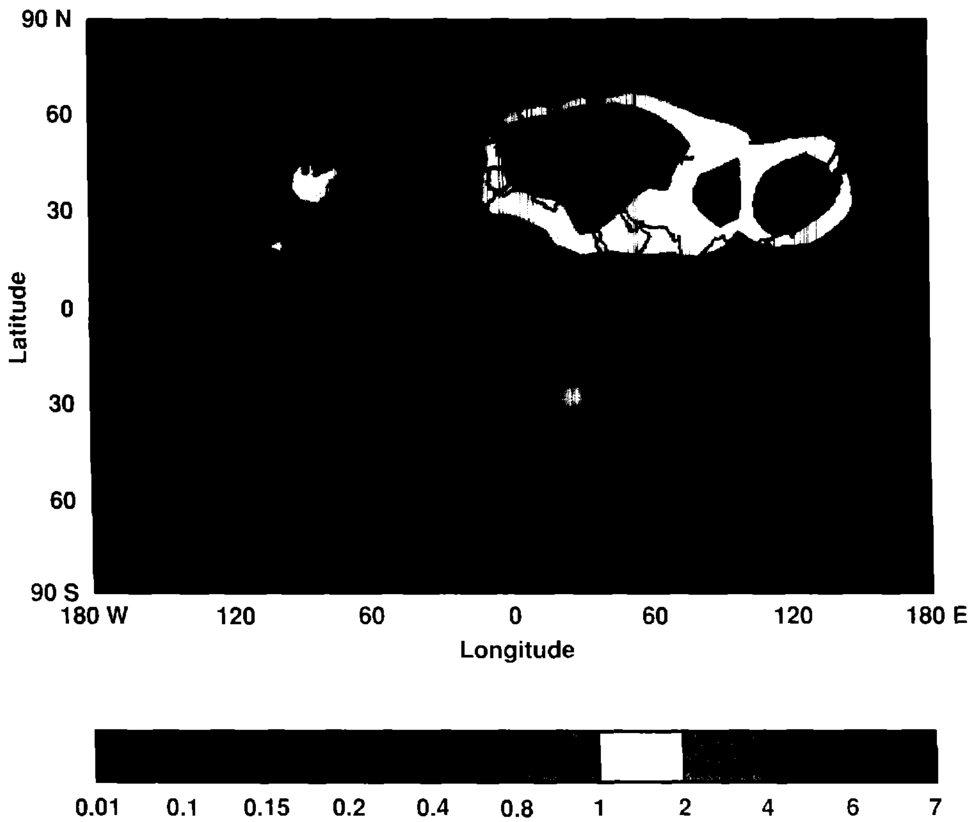

Figure 5. Integrated column loading of soot aerosol mass (mg C m^{-2}) from combustion sources. These aerosols absorb solar radiation, thereby counteracting to some extent the cooling by sulfate aerosols. Soot aerosol concentrations are highest over and downwind of industrialized nations.

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Global Atmospheric Trace Constituents and Their Effects on Ozone and Radiative Forcing

Donald J. Wuebbles, Group Leader

The Global Radiation, Chemical, and Dynamical Interactions Group studies the impacts of natural and human-related changes on ozone and the global atmosphere.

Over the last two decades, LLNL researchers have contributed substantially to the study of global atmospheric chemical and physical processes, and the interactions between these processes. Our research began in the early 1970s with studies of the natural and potentially perturbed stratosphere for the Department of Transportation's Climatic Impact Assessment Program. This program was aimed at determining the potential environmental effect of high-flying supersonic aircraft. We also conducted research on local and regional air quality for the National Science Foundation. In both cases, the studies focused on the development of computational models of atmospheric chemical, radiative, and physical processes. Since then, we have continued to expand our modeling capabilities.

One- and two-dimensional models of the global atmosphere developed at LLNL have been and are being used in a wide range of applications. The goals of these studies are to better understand the processes controlling the troposphere and stratosphere and to determine the past, present, and future impacts of human activities on atmospheric structure. Many studies are related to concerns about global ozone and the climatic effects of chemical processes.

We have made significant contributions, often with lead authorship responsibilities, to major national and international assessments related to ozone and climate change. These assessments are used by policymakers in their considerations of possible policy actions. In addition, the ozone depletion potential (ODP) concept developed at LLNL in 1981 is used extensively in national and international regulatory actions, such as the Montreal Protocol developed by the United Nations Environment Programme, in attempts to protect the ozone layer by reducing industrial production and emissions of chlorofluorocarbons (CFCs) and Halons. We also contributed to the development of a global warming potential (GWP) concept at the request of policymakers through the international Intergovernmental Panel on Climate Change. This concept determines the relative climatic effects of emissions of other greenhouse gases with respect to the effects of emissions of carbon dioxide (CO_2), the gas making the greatest contribution to the enhanced greenhouse effect.

Our studies have focused on global ozone and the effects of chemical processes on climate. The importance of these areas is highlighted by recent satellite and ground-based measurements, which indicate the following:

- Levels of total ozone at middle to high latitudes of both hemispheres are decreasing. Much of the decrease is in the lower stratosphere, and some is in the upper stratosphere.
- More than 50% of the total column of ozone is being destroyed over Antarctica each spring.
- Global tropospheric concentrations of ozone appear to be increasing.
- Global atmospheric concentrations of chemically and radiatively important greenhouse gases are continuing to increase.

The changes in ozone distribution are thought to be largely related to emissions of trace constituents from human activities. Human activities also appear to be largely responsible for increases in emissions and concentrations of climate-influencing greenhouse gases.

During the last several years, our research studies have examined a wide range of questions related to the global troposphere and stratosphere. We are using atmospheric models to determine the effects on tropospheric and stratospheric ozone due to (1) emissions of chlorofluorocarbons (CFCs), Halons (brominated halocarbons), methane (CH_4), and other surface-emitted trace gases, (2) current and potential emissions from aircraft, (3) atmospheric nuclear explosions, (4) volcanic eruptions, and (5) natural variations in the solar flux. We have also examined the relationship between recent trends in atmospheric ozone concentrations and temperature structure.

A major programmatic effort in our research is the scientific validation and analysis of data from the U.S. National Aeronautics and Space Administration (NASA) Upper Atmosphere Research Satellite. *This satellite is the first attempt to measure the global distributions of many of the gases influencing stratospheric* ozone. A recent study has examined the expected effects on stratospheric ozone and temperature from the Mt. Pinatubo volcanic eruption on June 15, 1991. Studies of aircraft effects have particularly focused on the potential environmental effects from a proposed fleet of high-flying, high-speed civil transport aircraft.

Climate-related studies have examined the effects of greenhouse gases, including ozone, on radiative forcing of climate. Other studies have explored the role of atmospheric chemical processes in climate chan Comparisons of the model-derived atmospheric str ture with available measurements are an import aspect of validating the models used in these studi The time and space domain being considered in c investigations is shown in Figure 1.

The group continues to develop advanced tools f *modeling atmospheric chemical and physical processe* This article describes our current modeling capabilitie and research activities.

Global Atmospheric Modeling

Chemical-Radiative-Transport Models

The LLNL zonally averaged, two-dimensional chemical-radiative-transport model currently determines the distributions of 54 chemically active atmospheric trace constituents in the troposphere and

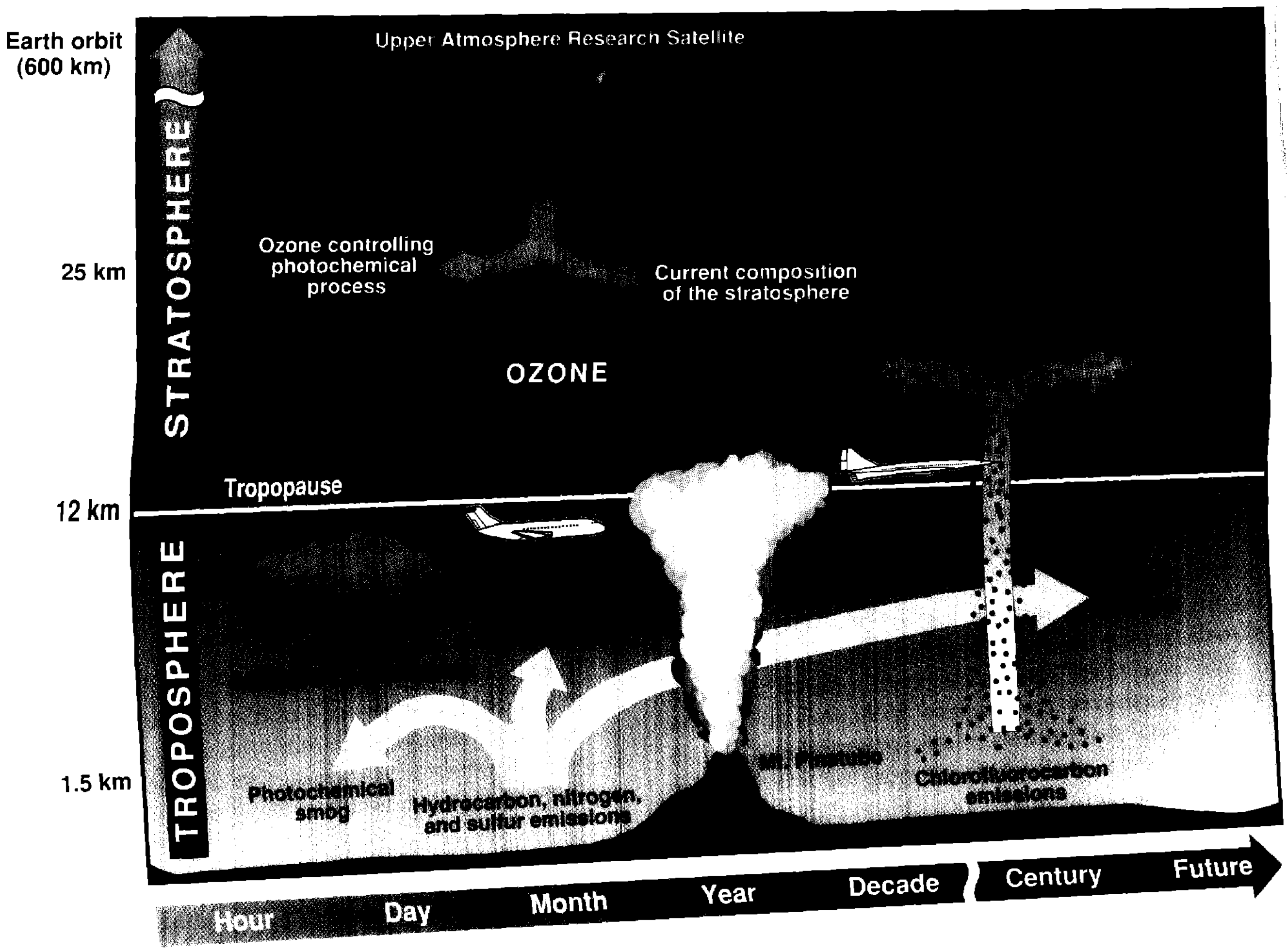

Figure 1. Schematic of the time and space domain of scientific investigations performed in our studies of atmospheric chemistry, radiative, and transport processes.

stratosphere. (When relevant hydrocarbons are considered, another 30 species are included.) The model domain extends from pole to pole, and from the surface to 60 km. The vertical resolution is 1.5 km in the troposphere and 3 km in the stratosphere. Figure 2 shows the processes affecting trace constituents that need to be considered in such a model.

The photochemistry in the model represents the tropospheric and stratospheric interactions of all of the relevant species containing oxygen, nitrogen, hydrogen, chlorine, and bromine. Photodissociation reactions resulting from interaction of these species with the actinic solar flux are included. Most of the thermal reaction rates are based on recommendations of the NASA panel of kinetics experts. Absorption cross-section information for photolysis was assembled from a variety of published sources. The photolytic loss rate constants are calculated by integrating the product of absorption coefficient, quantum yield, and solar flux over wavelength (175–735 nm). The exoatmospheric solar flux is based on satellite measurements. The solar flux is then calculated as a function of altitude, latitude, and season, including the effects of absorption by molecular oxygen and ozone and multiple molecular (Rayleigh) scattering. Absorption cross sections and quantum yields include temperature and pressure dependence where appropriate and available.

The model can be used to determine either the full diurnal variation or the diurnally averaged concentration of each calculated constituent. Because it is more computationally efficient, the diurnal-averaged version of the model is usually used. The nonlinearity of the photochemistry with respect to diurnal averaging is accounted for through the calculation of individual altitude, latitude, and seasonally varying factors for each photochemical process.

Because most atmospheric trace constituents are directly or indirectly influenced by atmospheric dynamics, proper representation of transport processes is crucial. In the two-dimensional model, the trace constituents are transported by both the zonal mean motions (winds) and the local deviation from the mean flow (termed eddy transport). The circulation field in the model is currently obtained diagnostically from a climatological temperature distribution. The zonal mean winds in the meridional and vertical directions are obtained using the net atmospheric heating rates. These heating rates are calculated from the distributions of temperature and chemical species; the calculation includes latent heating. Eddy-transport effects are estimated in the form of diffusion terms based on the principle of zonal mean momentum conservation. Future treatments of eddy transport will explicitly account for the effects of atmospheric wave activity by including a separate determination of the effects of planetary and gravity waves.

In the 1970s and the early 1980s, the one-dimensional chemical-radiative-transport model was the basic tool for studying global atmospheric chemical processes. The one-dimensional model represents the vertical transport of trace constituents by using a diffusion representation. This model was used to assess emissions from the proposed supersonic aircraft in the 1970s and in early analyses of the effects of CFC emissions on ozone. Because of its simplified treatment of atmospheric dynamics, the one-dimensional model has largely been supplanted by

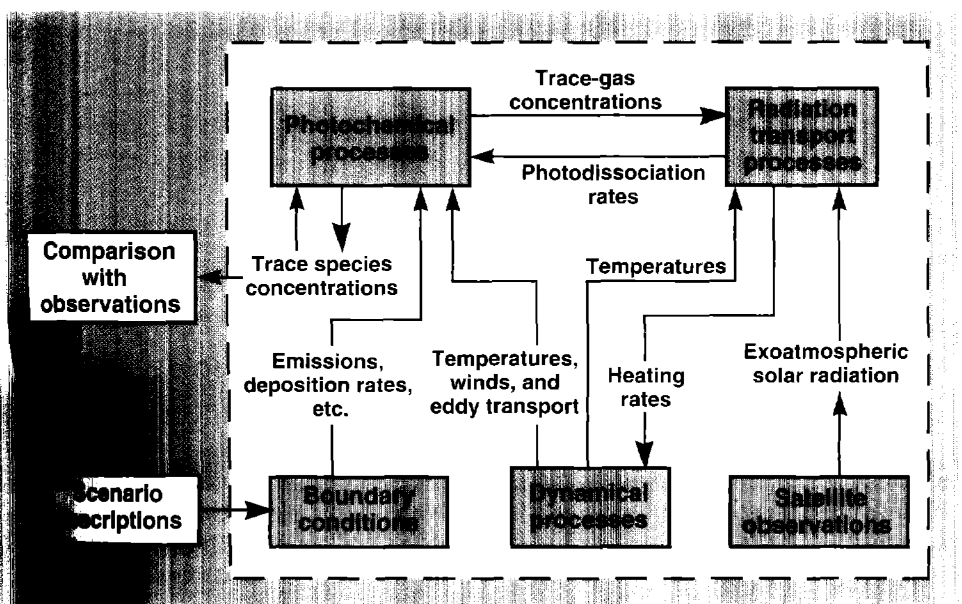

Figure 2. Processes important to the modeling of atmospheric chemistry and physics. These processes are included in our chemical-radiation-transport models.

the two-dimensional model. However, it contains the same complexity in treating atmospheric chemical processes as the two-dimensional model and is still used in chemistry sensitivity studies.

Radiative-Transfer Models

Radiative transfer is the process that establishes the energy balance between the Earth and free space and is an important energy-transfer mechanism within the atmosphere. There are many interactions between solar and infrared radiation and atmospheric molecules, clouds, and aerosols. Solar and infrared radiation also interact with the land and ocean surface. Figure 3 depicts many of these interactions.

We use radiative-transfer models as stand-alone diagnostic tools and as important components of more general atmospheric models. As diagnostic models, for example, radiative-transfer models are used to calculate the radiative forcing of the surface-troposphere system due to changes in trace-gas concentrations, aerosols, or clouds. Such calculations are an essential step in deriving global warming potentials (GWPs) for trace gases. GWPs provide an approximate index of the time-cumulative radiative effects of a unit emission of a specified trace gas relative to the comparable effect for CO_2.

As integral parts of global and regional chemistry models and of climate models, radiative-transfer models are used to calculate vertical profiles of net heating rates and chemical photodissociation rates. Calculations of solar heating rates and infrared cooling rates to obtain net heating profiles are a vital part of calculating the atmospheric circulation within global models. Calculations of photodissociation rates are fundamental to modeling atmospheric chemistry. In turn, accurate modeling of both atmospheric circulation and chemistry are important to modeling the effects of anthropogenic trace-gas emissions on ozone and global warming.

Solar Radiation Models

To capture the spectral detail needed for photodissociation calculations, our two-stream multiple-layer UV-visible model uses 126 wavelength bins between 175 and 735 nm. We chose the two-stream approach because of the requirements for computational efficiency placed on radiative-transfer models designed for inclusion in atmospheric chemistry models. In this approach, solar radiation is effectively divided into direct solar radiation, downward diffuse radiation, and upward diffuse radiation. The scattering of energy from the direct solar beam within each vertical layer is

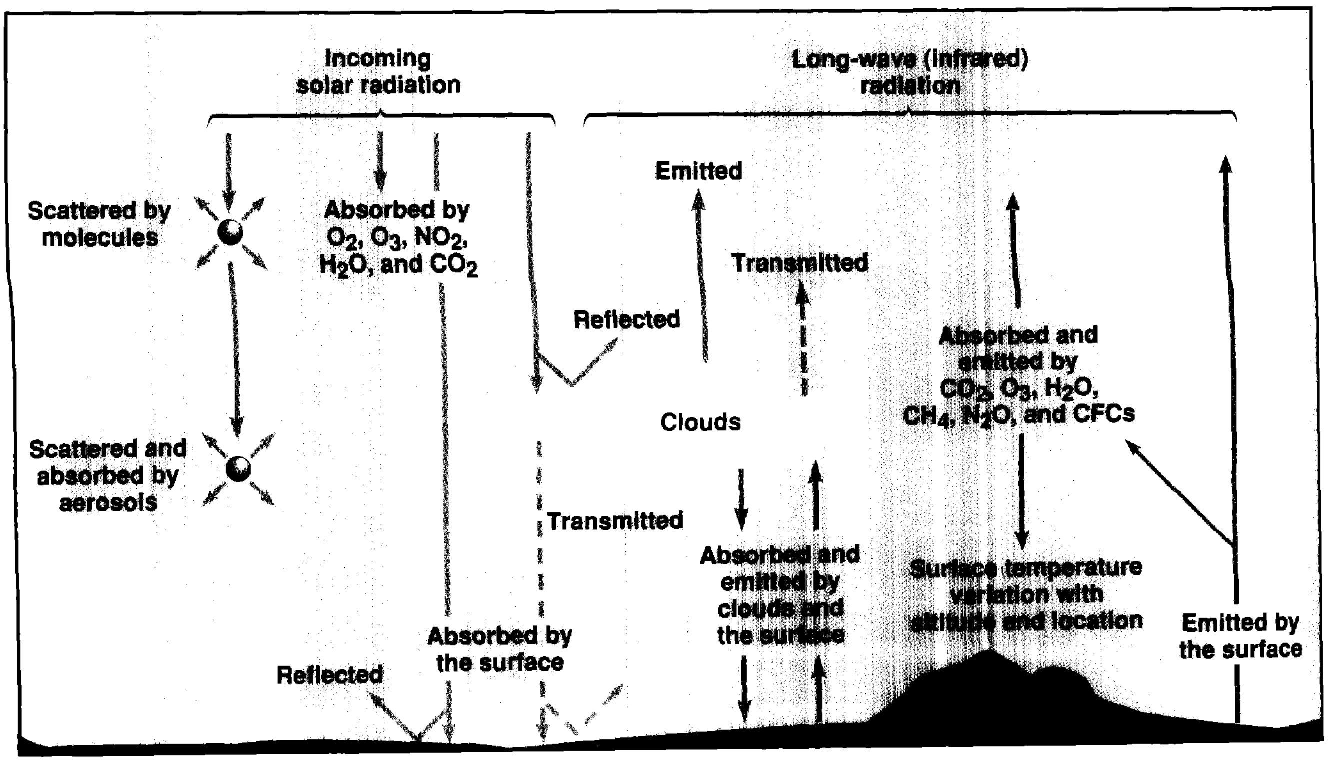

Figure 3. Interactions of solar and infrared radiation with the atmosphere and Earth's surface. These interactions are included in our radiative-transfer modeling.

treated using the delta-Eddington algorithm, which includes the dependence of scattering and absorption on the solar zenith angle. The scattering of diffuse radiation (i.e., previously scattered radiation) from each individual layer is modeled using the simpler Sagan-Pollack algorithm. Both algorithms allow inclusion of the bulk optical properties of clouds and aerosols. Finally, the adding method is used to calculate irradiances throughout the vertically inhomogeneous atmosphere.

Infrared Models

The infrared model that we have been using for several years includes absorption and emission by CO_2, O_3, and H_2O. It has been modified in recent years to improve the accuracy in the upper stratosphere. It is based on wide-band parameterizations fitted to line-by-line calculations. Inhomogeneous absorption paths are included by pressure- and temperature-weighted scaling of trace-gas-absorber amounts. The model provides for specification of fractional cloud cover within each vertical model layer. Separate fractions can be specified for convective (deep, overlapping) and randomly overlapped clouds.

Current efforts to improve our capabilities for modeling infrared radiative transfer are focusing on a new model using the correlated *k*-distribution technique. We have acquired a significant capability to calculate the absorption properties of common trace gases and have a state-of-the-art spectroscopic database readily available to us on our work-station network.

Development of Next-Generation Three-Dimensional Models

Future studies of the global climate system, including climate change, will include the important intercouplings of the atmosphere, oceans, and land ecosystems, including full consideration of atmospheric chemistry, in a three-dimensional model (longitude, latitude, and altitude). Present global-climate models utilize the available computer resources of supercomputers even without these couplings. Including the other features will require a computer several orders of magnitude more powerful than today's supercomputers. We are beginning to develop a new-generation atmospheric-chemistry/trace-species transport model of the global atmosphere to run on massively parallel computers. Future developments in these computers are expected to provide the needed computer power.

The next-generation chemical-transport model needs to be three-dimensional because of the uneven distribution of emission sources at the surface of the Earth, the range of time constants in the chemical system, and the importance of meteorological processes in the transport of trace constituents. This model must also have high resolution to accurately treat sharp chemical and transport gradients. The model will be developed to simulate chemical and transport processes on a range of spatial scales, from regional to global, and temporal scales, from days to decades. It will contain accurate representations of important sub-scale processes, including convective cloud transport and boundary-layer processes. Heterogeneous chemical processes (reactions of gases with particles) on aerosols and clouds will be included along with homogeneous gas-phase chemistry.

This new modeling capability will allow for fully interactive atmospheric chemistry with the dynamics of advanced global-circulation models to improve our understanding of processes affecting atmospheric trace constituents. It will provide the capability for complete coupling of atmospheric chemical, radiative, and dynamical processes to ocean models and land-ecosystems models for investigating the full range of interactions in the Earth system. This type of modeling is needed to understand and predict the effects of natural and human-related changes imposed on the Earth's climate system. These interactive capabilities are likely to be extremely important in evaluating past and future changes in climate.

The new model could also be run as a stand-alone module for studies of chemistry and transport processes in the troposphere and stratosphere. Such calculations could be initiated in conjunction with observed or data-assimilated wind fields for more accurate analyses of particular regimes or events.

Selected Research Projects and Studies

CFCs, Halons, and the Stratosphere

CFCs and Halons (bromofluorocarbons) are industrially produced compounds that have high vapor pressures at room temperature and are nearly inert in the troposphere. These and other properties make them extremely useful in their applications (refrigeration, foam-blowing, degreasing, fire fighting, etc.). These properties also result in long lifetimes (years to decades to centuries) if the compounds are released into the atmosphere.

Once in the atmosphere, other properties become of prime importance: the compounds contain chlorine or bromine, they are decomposed by UV radiation of wavelengths that penetrate into the stratosphere, and they absorb light efficiently in the region of the infrared at which the Earth radiates into space. The atmospheric consequences include (1) significant participation in ozone-controlling photochemistry in the stratosphere, and (2) a non-negligible contribution to the atmosphere's infrared radiation trapping (greenhouse effect). This latter property is discussed below.

As stated above, numerical models play an important role in research on the atmospheric impacts of emissions. The models represent the atmospheric physics and photochemistry that determine the behavior of CFCs and Halons in the atmosphere. For almost two decades, we have been a leading research group in the study of the effects of these compounds on stratospheric ozone. Our two-dimensional model continues to be a primary tool in this field. Models such as ours are used to (1) interpret observations of the atmosphere, (2) infer or predict behavior of trace constituents in the current atmosphere and under projected future conditions, and (3) highlight observations not explained by current theories of stratospheric processes.

Predicting the response of the atmosphere to as-yet-unreleased CFCs or proposed alternative chemicals is an area of continuing model development in our group. Our model is tested and improved by inclusion of new experimental information on the properties of CFCs and related trace constituents, better representations of atmospheric dynamics, and comparison against CFCs and their effects observed by surface monitoring, balloons, aircraft, and satellites.

With knowledge of the relevant properties of CFCs, Halons, and the proposed alternatives to CFCs and Halons, the model can predict atmospheric effects of large-scale production of these compounds. An important example of this use of the model is calculation of the ozone depletion potentials (ODPs) for chlorine- or bromine-containing alternatives; these ODPs then represent an estimate of the benefits of specific replacements for CFCs currently produced. The ODP calculation considers, in detail, the global spatial and temporal distribution of composition, temperature, and solar radiation. This information is used to determine the expected atmospheric distribution of a compound, its lifetime, the distribution of the release of atomic chlorine or bromine, and its subsequent effects. ODPs are used extensively in both national and international policymaking related to controlling emissions of CFCs and Halons. Our group originally developed the ODP concept (Wuebbles, 1981, 1983), has continued to actively participate in international evaluations of ODPs and their uncertainties, and is playing an important role in evaluating new compounds of interest to the policymakers (e.g., compounds being considered as replacements for CFCs and Halons).

We evaluated a number of compounds for the recent international scientific assessment of stratospheric ozone sponsored by the United Nations Environment Programme and the World Meteorological Organization (WMO, 1991). Table 1 shows the ODPs calculated with the two-dimensional chemical-radiative-transport model for a number of compounds included in the WMO (1991) measurement. Included in this list are the CFCs, Halons, and other compounds already being used extensively, plus a number of the compounds being considered as replacements for CFCs and Halons in a variety of uses. The major CFCs and Halons all have large ODP values. The U.S. Clean Air Act currently calls for eliminating the production of any compound with an ODP greater than 0.2.

The Upper Atmosphere Research Satellite (UARS)

We are theoretical investigators in the NASA-sponsored UARS research program. UARS, which was launched in September 1991, is primarily dedicated to the understanding of stratospheric and mesospheric processes, with particular emphasis on the chemistry influencing stratospheric ozone. It represents an early element of the NASA Mission to Planet Earth, and, with the de-emphasis on stratospheric chemistry in planning for the future Earth Observing System (EOS), the data UARS collects will be the most comprehensive set of satellite data available until after the turn of the century. Unlike previous satellite programs, the participation of theoretical and numerical atmospheric modeling groups such as ours has been part of UARS throughout the planning, design, and execution phases. Our group has the lead responsibility on the UARS Science Team for theoretical data analysis from the standpoints of photochemistry and the interactions of radiation, dynamics, and chemistry.

Using our model as an assimilation tool for previous satellite data, before launch we produced (1) a "climatology" of trace-species distributions, which serves as a first-guess species profile for the instrument data-retrieval algorithms, and (2) an initial "sanity" check on the retrieved profile. After launch, the UARS instruments began taking measurements, and instrument investigators are evaluating and attempting to validate the measured radiances. Validated algorithms will becoming available for the operating species-profiling instruments, and we are beginning studies using the evaluated data. Some of the studies now underway relate to (1) the ozone balance in the upper stratosphere, where ozone is under direct photochemical control, (2) the possibility of observing the effects of aerosol-surface interactions outside of the winter polar regimes, and (3) the effects of the Mt. Pinatubo eruption of June 1991 on the stratosphere.

Emissions from Aircraft

The aircraft industry is showing renewed interest in the development of supersonic high-flying aircraft for intercontinental passenger flights. There is confidence that such high-speed civil transports (HSCTs) can be designed and that they will be economically viable if they are environmentally acceptable. It is important to establish the potential for such environmental problems early in the aircraft design. As indicated above, we have a long history of studying potential aircraft-emission effects on the stratosphere. Past studies performed with LLNL models of global atmospheric chemical, radiative, and transport processes showed that stratospheric ozone concentrations could decrease substantially because of nitrogen oxide emitted by aircraft flying in the stratosphere (Johnston et al., 1989). The decrease depends on fleet size and the magnitude of the engine emissions.

Recent calculations (Kinnison and Wuebbles, 1992), which include the effects of chemical reactions occurring on background aerosols and aerosol concentrations perturbed by major volcanic eruptions (e.g., Mt. Pinatubo), suggest that the potential decrease in ozone from nitrogen oxide emissions may be less than calculations excluding these effects. This heterogeneous chemistry between atmospheric gases

Table 1. Derived ozone depletion potentials (ODPs) for [illegible] including chlorofluorocarbons (CFCs), halons, and [illegible] CFCs and halons. ODPs are defined relative to CFC-11; [illegible] the ODP of CFC-11 is 1.0.

Compound	Chemical formula	ODP
CFCs		
CFC-11	$CFCl_3$	[illegible]
CFC-12	CF_2Cl_2	[illegible]
CFC-113	$CFCl_2CF_2Cl$	[illegible]
CFC-114	CF_2ClCF_2Cl	[illegible]
CFC-115	CF_2ClCF_3	[illegible]
HCFCs		
HCFC-22	CF_2HCl	[illegible]
HCFC-123	CF_3CHCl_2	[illegible]
HCFC-124	CF_3CHFCl	[illegible]
HCFC-141b	CH_3CFCl_2	[illegible]
HCFC-142b	CH_3CF_2Cl	[illegible]
HCFC-225ca	$CF_3CF_2CHCl_2$	[illegible]
HCFC-225ca	CF_2ClCF_2CHFCl	[illegible]
Halons		
H-1301	CF_3Br	[illegible]
H-1211	CF_2ClBr	[illegible]
H-1202	CF_2Br_2	[illegible]
H-2402	CF_2BrCF_2Br	[illegible]
H-1201	CF_2HBr	[illegible]
H-2401	CF_3CHFBr	[illegible]
H-2311	$CF_3CHClBr$	[illegible]
Other compounds		
Carbon tetrachloride	CCl_4	[illegible]
Methyl chloroform	CH_3CCl_3	[illegible]
Methyl bromide	CH_3Br	[illegible]

and particles is likely to be extremely important in evaluating the potential environmental effects of the HSCTs. As an example, we investigated the effects of ozone from a fleet of 500 aircraft flying at Mach 2.4, corresponding to a cruise altitude of about 18 km. With gas-phase chemistry, we calculated a 1.4% global decrease in ozone. Including heterogeneous chemistry reduced the effect to a 0.2% decrease in global ozone.

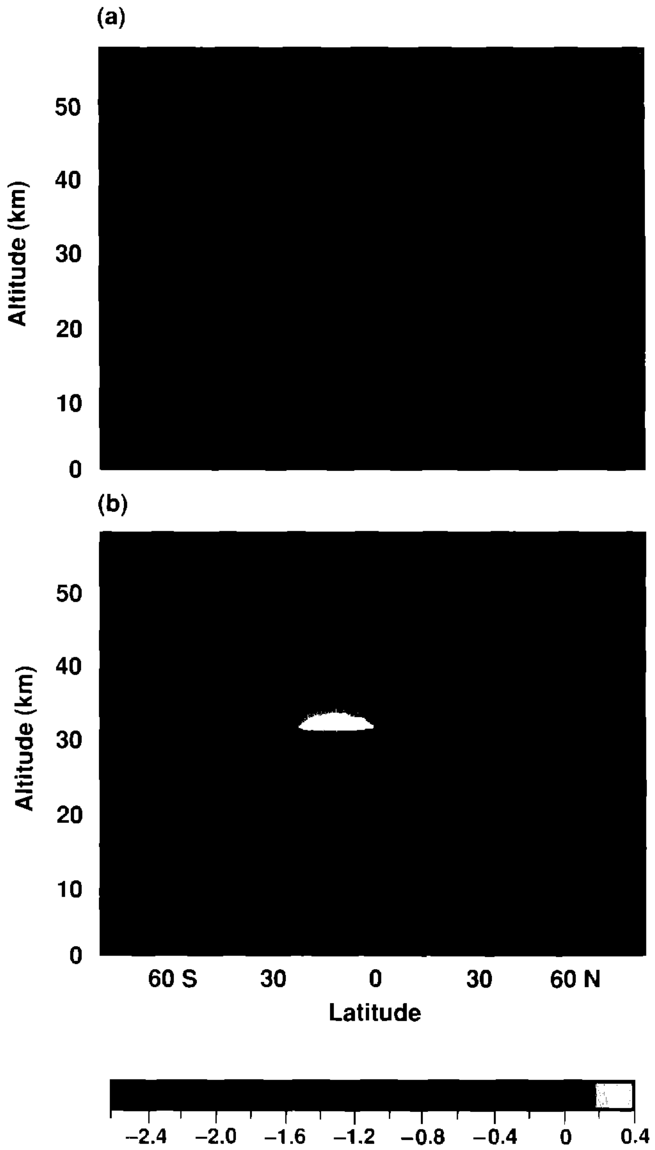

Figure 4. Model-calculated percent change in ozone in **(a)** September 1991, and **(b)** October 1991, due to the effects of the Mt. Pinatubo eruption, which occurred on June 15, 1991. The percent changes are relative to the same months evaluated with no volcanic emissions.

There is also concern that emissions of nitrogen oxides from current subsonic aircraft fleets may be increasing tropospheric ozone. In the troposphere, nitrogen oxide emissions enhance the production of ozone via complex chemical-smog reactions. Model calculations suggest that over the last decade, ozone in the middle to upper troposphere may have increased by 3 to 5%. Because ozone is a greenhouse gas, the potential climatic effects are also being investigated.

Volcanic Eruptions: Mt. Pinatubo

Recent eruptions from Mt. Pinatubo (June 15, 1991, 15.14°N., 120.35°E.) produced a stratospheric aerosol cloud that was observed at altitudes between 18 and 28 km. Although the latitude distribution of Mt. Pinatubo aerosol is predominantly equatorial, observations suggest that some material has reached northern mid-latitudes, primarily in the lower stratosphere. Aerosol optical thickness, in a zone about 40° wide straddling the equator, has consistently been observed at double the maximum expected background values. In addition, chemical reactions occurring on the surface of these aerosols are believed to alter the chemical composition in the global atmosphere. These perturbations to the ambient aerosol burden are expected to have significant chemical and radiative effects; their net effect would be to reduce ozone where aerosol loading is increased.

We are using the LLNL two-dimensional chemical-radiative-transport model of the troposphere and stratosphere, in conjunction with the best available Mt. Pinatubo aerosol data, to study the chemical and radiative effects on ozone, concentrations of other trace gases, and temperature distributions (Kinnison et al., 1992). Preliminary results suggest that the Mt. Pinatubo eruption decreased ozone in the equatorial region, at 25 km, by more than 2% (Figure 4). The aerosol amounts used in the model for these months are based on satellite measurements. Currently, changes in distributions of trace species derived from the model as a response to Mt. Pinatubo are being compared with distributions of constituents measured by UARS.

Tropospheric Chemistry

Several of our research projects are focused on tropospheric chemistry. The emphasis of these studies is to understand the effects of methane, higher hydrocarbons, carbon monoxide, and nitrogen oxides on global tropospheric ozone and hydroxyl. The oxidizing capacity or self-cleansing capability of the troposphere is largely determined by the concentrations of ozone and hydroxyl. For example, the primary destruction of methane, higher hydrocarbons, carbon monoxide, sulfur dioxide, and many other chemicals occurs through their reaction with hydroxyl. Therefore, hydroxyl plays an important role in determining the atmospheric concentration of these compounds. Because many of these compounds, including ozone, are greenhouse gases, their atmospheric concentrations are also important to determining the radiative forcing on climate. Our studies focus on obtaining a better understanding of the oxidizing capacity of the atmosphere, on how surface emissions of methane and other compounds affect this capacity, and on how climatic forcing may be affected by these chemical interactions (Wuebbles and Tamaresis, 1992). We are also interested in evaluating the effects of nitrogen oxide emissions on tropospheric ozone from existing and future commercial-aircraft fleets.

We are extensively modifying our two-dimensional model of the global atmosphere to improve its treatment of tropospheric chemical and physical processes. For example, we recently added a detailed representation of nonmethane hydrocarbon chemistry to the model. We are in the process of analyzing the complete chemical mechanism against smog-chamber experiments to evaluate the capability of the model to predict ozone produced from interactions of hydrocarbons and nitrogen oxides. We also improved the treatment of cloud effects on tropospheric photochemistry and added a new climatology for tropospheric clouds by type, amount, and structure.

Greenhouse Gases and Climate Change

The increasing atmospheric concentrations of CO_2 and other trace gases are potentially one of the most important environmental questions facing humankind. The increasing concentrations are largely the result of energy use and other human-related activities. As these concentrations change, the radiative forcing on climate changes. Chemical interactions in the atmosphere can affect other radiatively important gases and lead to further effects on radiative forcing.

Our research is aimed at determining the potential effects of these changes on climate (Lacis et al., 1990; Wuebbles, 1992). We are currently studying the effects of CO_2-induced climatic change on global chemistry, the role of non-CO_2 trace constituents on climatic change, and the role these gases may play in amplifying or moderating the climatic effects of increased CO_2. Of particular interest are the indirect influences of CFC and Halon on stratospheric ozone, and the effects of methane on tropospheric ozone and stratospheric water vapor. New atmospheric modeling capabilities are being developed to study these processes. We are performing budget analyses of the emissions, sources, and sinks of these gases to improve the capability for projecting future concentrations.

Other studies are aimed at refining and examining uncertainties associated with the global warming potential (GWP) concept, which we helped develop for policymakers as part of an international climate assessment for the Intergovernmental Panel on Climate Change in 1990 (IPCC, 1990, 1992). GWPs provide a means of comparing the potential effect of emissions of a greenhouse gas relative to carbon dioxide, the greenhouse gas of most concern because of its rapid increase in concentration. The GWP for a greenhouse gas is defined as the time-integrated commitment to climate forcing from the instantaneous release of a unit mass of the gas relative to the climate forcing from the release of a unit mass of CO_2. Table 2 shows the GWPs calculated at LLNL for several integrated time horizons using the same approach as used in the IPCC studies. A recent study (Wuebbles et al., 1992) examines the effects of several uncertainties in the carbon cycle, the background atmosphere, and the lifetimes of gases assumed in the prior calculations of GWP. For example, the IPCC's evaluations of GWPs did not attempt to account for the possible sinks of CO_2 that could balance the carbon cycle and produce atmospheric concentrations of CO_2 that match observations. Use of a balanced carbon cycle produces up to a 20% increase of the GWPs for most trace gases compared to the IPCC values.

Radiative Diagnostics

A major focus of our continuing radiation-transfer modeling efforts is the development of a new infrared radiative-transfer model based on the correlated *k*-distribution technique. When complete, this model will provide a standardized framework and methodology for the inclusion of a larger number of radiatively active trace gases. The model is based on absorption data accurate into the upper stratosphere. It also is specifically designed to handle both time-varying temperature profiles and time-varying trace-gas concentrations. It is designed both to be included in atmospheric-chemistry models and for stand-alone radiative diagnostics. We are currently validating a prototype version of this model against more detailed line-by-line calculations.

We are studying the effects of seasonally and latitudinally varying cloud parameterizations on direct and indirect radiative diagnostics. Direct diagnostics include outgoing solar and infrared radiation at the top of the atmosphere. Indirect effects include changes in the rates of photolysis reactions and trace-gas concentrations.

Future Plans

Our research will continue to focus on achieving a basic understanding of the global atmosphere and on determining the impacts of human activities and natural perturbations. We expect that the new three-dimensional chemical-transport model will be utilized for limited studies within the next few years. However, extensive use of this model will require much larger computer resources than are currently available. Until then, the two-dimensional model will continue as the primary tool in our studies of tropospheric and stratospheric processes. Development of these models will continue to focus on achievement of accurate treatments of chemical and physical processes for diagnostic and prognostic research studies.

Tropospheric chemistry and the effects of human-related emissions on the troposphere are likely to be more emphasized in future research. As the three-dimensional model becomes available, there will be emphasis on interactive chemistry-climate studies and on studies examining the chemical couplings and interactions between the atmosphere, oceans, and biosphere. The capability of the new chemical-transport model to couple with other models of the atmosphere, oceans, and biosphere will be crucial to these studies.

Group Members

The work described in this article was performed by, or under the auspices of, the Global Radiative, Chemical, and Dynamical Interactions Group. Scientists involved include Donald J. Wuebbles (Group Leader), Woo-Kap Choi, Peter S. Connell, Raymond D. Gentry, Keith E. Grant, Allen S. Grossman, Susan Kemball-Cook, Douglas E. Kinnison, Thomas A. Kuczmarski, John E. Mak, Mary Ann Mansigh, Kenneth O. Patten, Douglas A. Rotman, John S. Tamaresis, and Raymond L. Tarp.

We are participating with a number of researchers from other laboratories, universities, and institutes whose contributions may not be fully reported here. Appendix B provides a brief summary of these interactions.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division; the Department of Energy, Assistant Secretary for Domestic and International Energy Policy, Program Analysis, Office of Environmental Analysis; the National Aeronautics and

Table 2. Equilibrium global warming potentials (GWPs) using the IPCC (1992) impulse response function and atmospheric lifetimes.

Gas	GWP at time horizon (yr) 20	50	100	200	500
CO_2	1.0	1.0	1.0	1.0	1.0
CH_4	34.3	18.9	11.2	6.9	3.8
N_2O	254.0	269.0	266.0	239.0	165.0
CFC-11	[illegible]	4100.0	3370.0	2400.0	1360.0
CFC-12	7810.0	7330.0	7090.0	6180.0	4100.0
HCFC-22	[illegible]	2580.0	1580.0	960.0	535.0
CFC-113	[illegible]	4670.0	4490.0	3850.0	2510.0
CFC-114	5960.0	6600.0	6950.0	6960.0	5780.0
CFC-115	5390.0	6210.0	6970.0	7620.0	8460.0
HCFC-123	331.0	157.0	93.1	56.4	31.2
HCFC-124	1540.0	776.0	453.0	279.0	154.0
HFC-125	5450.0	4430.0	3350.0	2230.0	1240.0
HFC-134a	3180.0	1940.0	1180.0	725.0	401.0
HCFC-141b	1810.0	1020.0	609.0	372.0	206.0
HCFC-142b	3930.0	2820.0	1830.0	1140.0	628.0
HFC-143a	4670.0	4470.0	3820.0	2920.0	1640.0
HFC-152a	524.0	248.0	145.0	[illegible]	49.1
CCl_4	1770.0	1580.0	1250.0	864.0	478.0
CH_3CCl_3	351.0	173.0	101.0	62.0	34.2
CF_3Br	5530.0	5460.0	4880.0	3880.0	2270.0

Space Administration; the Environmental Protection Agency; the Gas Research Institute; and McDonnell Douglas Corporation.

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Modeling Global Climate Change

Michael C. MacCracken, Group Leader

The Climate and Climate Change Group focuses on improving understanding of the potential for human activities and natural events to alter the climate. Projects range from developing global climate models to preparing cross-disciplinary curriculum materials for grades K–12.

The Climate and Climate Change Group is developing global climate models to predict the extent and nature of potential climatic changes that may occur as a result of human activities and natural events altering the composition of the atmosphere and the surface vegetation. Through our research efforts, we provide program support to the U.S. Department of Energy (DOE) and outreach to the academic research community.

Over the last decade, we have significantly advanced our modeling capabilities. In the 1970s and early 1980s, our primary tool for investigating climate and climate change was a two-dimensional climate model that represented latitude-altitude variations (MacCracken and Ghan, 1988). This model was used in a range of diagnostic and application studies to examine the potential climatic effects of perturbations to the climate, such as increases in carbon dioxide, tropical deforestation, desertification, Arctic soot, and the El Chichón volcanic eruption. During the mid-1980s, the potential threat of severe climatic cooling from the smoke generated by a global nuclear war (an effect referred to as "nuclear winter") led to a major extension of our climate modeling studies. Our two-dimensional models were expanded to three-dimensional general circulation models (GCMs), and we performed the first global simulation that could interactively calculate the transport of smoke and the resulting climatic perturbations (Ghan et al., 1988). Although these calculations suggested that the temperature decreases would be less than others had originally proposed, they also suggested that the reduction in precipitation and the interference with the monsoon circulation could be significant.

Our more recent model development activities have included transfer of the models to massively parallel computers (MPCs); model application studies to estimate the climatic changes caused by natural and anthropogenic perturbations to the atmosphere (e.g., volcanic eruptions and the release of greenhouse gases); and analyses to examine the role of particular processes in contributing to climatic change. In an important educational augmentation of our program, we are developing, testing, and disseminating a K–12 cross-disciplinary curriculum on greenhouse-induced climatic change.

Global Modeling Using MPCs

Climate simulation is a computer intensive activity. In fact, even with today's supercomputers, the resolution and physical comprehensiveness of atmospheric and oceanic models are well below what is needed to represent and project climatic conditions on regional scales. With support from the DOE Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) program, we are currently involved in two major projects to transfer climate models to MPCs. We are adapting both atmospheric and oceanic models for use with the new generation of MPCs, which are expected to achieve thousand-fold increases in throughput (speedups) using hundreds to thousands of processors acting in parallel. These models will become the framework for a coupled-Earth system model that will include representations of the atmosphere-ocean-land-biology system.

Oceanic and Atmospheric GCMs

In cooperation with researchers at the University of California, Los Angeles (UCLA) and Colorado State University (CSU), we are converting the UCLA/CSU atmospheric GCM to MPCs using a two-dimensional domain decomposition message-passing (DDMP) paradigm for parallelization. In cooperation with researchers at the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric

Administration (NOAA), we are adapting the GFDL oceanic GCM using a similar approach to parallelization. Basically, this approach assigns groups of adjacent vertical columns in the atmosphere or ocean to a single processor and then relies on interprocessor communication to transfer the information needed to calculate the horizontal transport terms. Scaling laws have been developed from our initial transfers of these models to the BBN TC2000 MPC at LLNL. As indicated in Figure 1, these scaling laws show that highly efficient use of the many multiple processors can be achieved. We plan to couple the massively parallel versions of the atmospheric and oceanic GCMs and explore the means of optimizing computational performance.

Building an Earth Systems Model

We have initiated a three-year Earth systems modeling project to develop and test a coupled model representing the chemistry, dynamics, thermodynamics, and biology of the atmosphere-ocean-land system. This model will incorporate a reasonably comprehensive set of the important processes and interactions. Figure 2 shows a schematic diagram of an Earth Systems Model (ESM) and the processes coupling the system components. Although not all processes coupling the system components, or even all processes within each component, can be accurately represented based on current understanding, we hope that coupling of the components into a prototype ESM will allow us to explore the strengths and weaknesses of current process representations.

We will begin coupling with the UCLA/CSU atmospheric GCM and the GFDL oceanic GCM. A suite of models are now being assembled or developed to represent the hydrology and biology of the land surface. Conceptually, our ecosystems model will have several levels in both space and time. To properly treat ecosystem variations, levels will range from a fine-grid-scale model (e.g., 0.5° latitude and longitude resolution) that includes processes determining the long-term evolution of vegetation types to a GCM-grid-scale model that includes processes controlling the hourly flux exchanges between the surface and atmosphere. We are designing our terrestrial ecosystem model (TERRA) to represent short-term processes controlling the surface moisture balance, the seasonal variation in vegetation cover, and the uptake, production, and emission of compounds containing carbon, sulfur, and nitrogen. To represent the interactions of climate and vegetation cover and type, we are developing the HABITAT model.

To approach the challenging task of coupling these different models and their diverse set of processes, we are initially coupling various subsets of the system's components to develop and test the most critical linkages. We are focusing first on examining the following linkages:

- Dynamics and thermodynamics of the atmosphere and ocean.
- Chemistry of the atmosphere and the biogeochemistry of the oceans and land.
- Hydrology and ecology of the land surface and dependence on the atmospheric state.

Progress on the second task is described in the "Tropospheric Chemistry and Climate Change" article earlier in this report. With support from other resources, we are exploring a fourth critical linkage, namely the coupling of the chemistry and the dynamics and thermodynamics of the atmosphere (see "Global Atmospheric Trace Constituents and Their Effects on Ozone and Radiative Forcing" article). This work will be done in parallel with the extensive monitoring, modeling, and process studies now

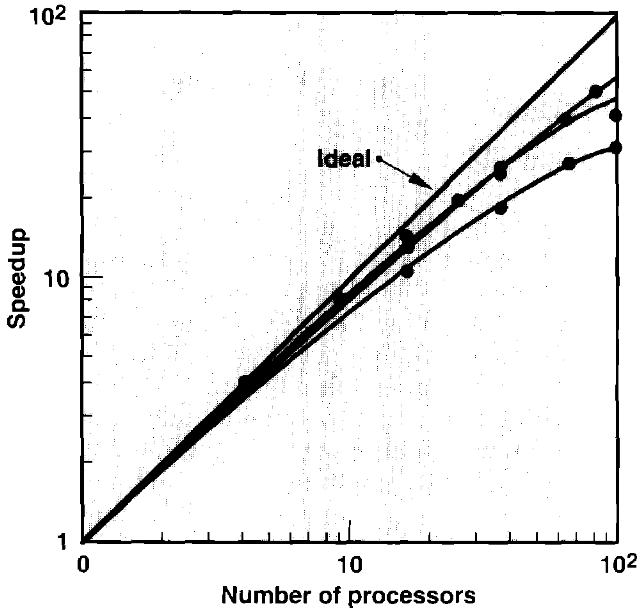

Figure 1. Parallel performance of the UCLA/CSU atmospheric general circulation model and the two-dimensional domain decomposition message-passing (DDMP) approach to parallelization on the BBN TC2000 massively parallel computer. The black line shows the ideal speedup. The blue curved lines show the predicted performance for three types of experiments based on DDMP scaling, and the data points represent observed performance for the case of 4° × 5° horizontal resolution.

underway as part of the national scientific effort on behalf of the U.S. Global Change Research Program (GCRP); we expect to contribute to the GCRP's goal of developing predictive ESMs.

To permit linking of the atmospheric, oceanic, and terrestrial components of the ESM, we are developing a framework that will readily allow the communication and exchange of information. The framework is beginning with the atmospheric and oceanic GCMs and is being designed to be easily expandable to include both the separate atmospheric chemistry model that is being developed as part of the CHAMMP program (discussed in "Global Atmospheric Trace Constituents and Their Effects on Ozone and Radiative Forcing" article) and the land surface and terrestrial ecosystem models.

Model Verification

Our model verification studies involve evaluation and analysis of the performance of both atmospheric and oceanic GCMs. Our focus is on the most critical processes in each, namely cloud-radiation interactions in the atmospheric GCM and heat transport from the upper layers into the abyssal deep ocean in the oceanic GCM.

Changing Cloud Properties with Global Warming

The direct radiative effects of changing concentrations of major greenhouse gases (e.g., carbon dioxide, methane, and chlorofluorocarbons) have been reasonably well quantified. The complex feedbacks and interactions that are associated with the response of climate to the radiative perturbations, on the other hand, are not nearly as well understood. Perhaps most complex among the feedbacks are the radiative effects of clouds. As the Earth's climate changes, the amount, distribution, and optical properties of clouds, which together control their radiative effects, may also change, in a manner that is as yet poorly understood. Preliminary studies, however, indicate that these changes can significantly amplify the initial radiative forcing of the increase in greenhouse gases.

In one study of cloud feedback, we modified the LLNL version of the Community Climate Model (CCM1) from the National Center for Atmospheric Research (NCAR). In this modified model the cloud optical properties (i.e., albedo, emissivity, and absorptivity) were no longer prescribed but were free to vary with the liquid-water content of the cloud. Figure 3 shows the strong dependence of cloud albedo on the liquid-water content. This relationship implies that changes in aerosol concentration or in the precipitation

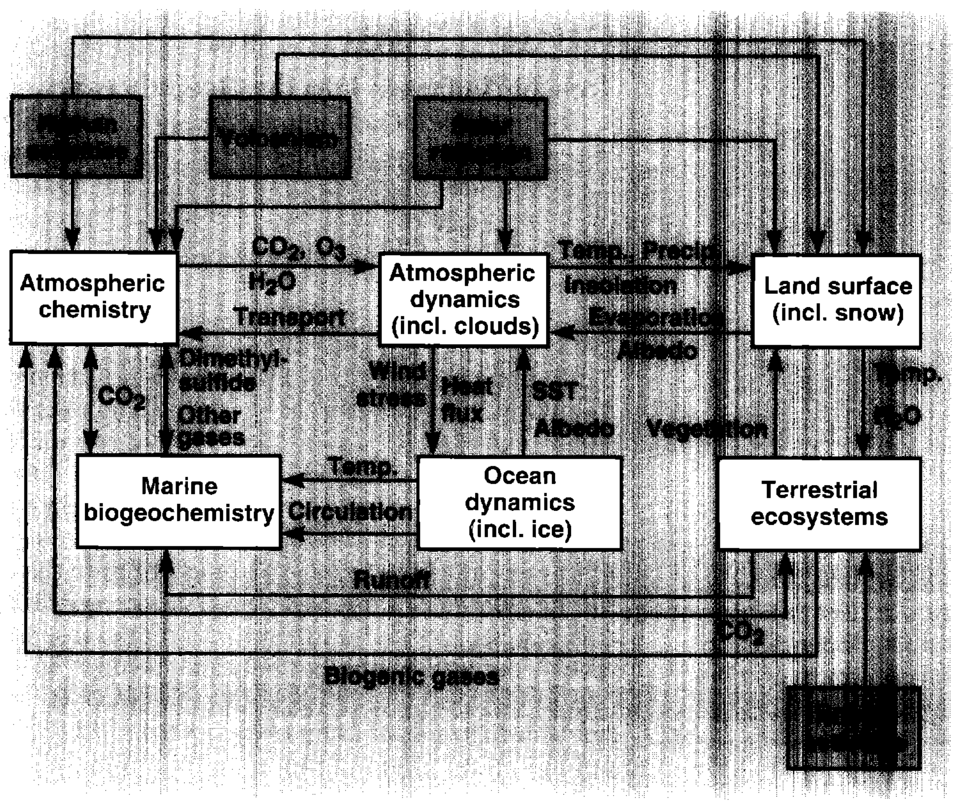

Figure 2. Our Earth Systems Model (ESM) will treat the physical, chemical, hydrological, and biological interactions of the atmosphere, oceans, and land surface.

rate could have climatic feedbacks. We found that this liquid-water feedback of the cloud was comparable in importance to the feedbacks associated with changes in cloud amount and distribution. We performed a set of controlled model experiments and determined that as the climate warms in this model, the general increase in the liquid-water content of each cloud layer has an effect on the net radiative balance that is partially offset by the radiative effect of an upward shift in cloud altitude. Also, the effects of clouds on long-wave radiation generally tend to cancel the effects on short-wave radiation (e.g., an increase in global cloud cover decreases the amount of short-wave radiation absorbed by the Earth but also reduces the outgoing long-wave radiation). Consequently, the net cloud feedback represents a residual of several offsetting effects; the net cloud feedback is nevertheless large enough to nearly double the response of the simulated climate to the direct radiative forcing (Taylor and Ghan, 1992).

We studied other potentially important feedback processes that could amplify the direct radiative forcing caused by the increase in greenhouse gases. It has been suggested that global warming would reduce the extent of sea ice and snow at high latitudes, which would increase the amount of short-wave radiation absorbed by the Earth and amplify the warming. This interaction involving changes in the surface reflectivity caused by changes in temperature is called sea-ice albedo feedback or snow albedo feedback, depending on the surface. In one study (Covey et al., 1991), we obtained an upper-limit estimate of the importance of the sea-ice albedo feedback. We found that if all of the sea ice were to melt, the radiative effect would be about half the effect of doubling the concentration of carbon dioxide in the atmosphere. The local effects at high latitudes were, of course, many times larger than this.

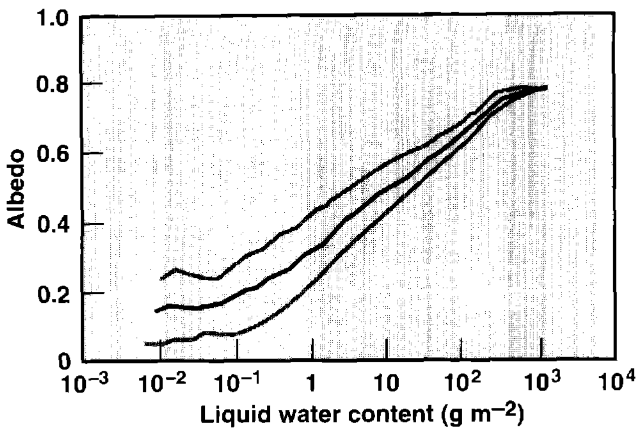

Figure 3. The albedo (i.e., the fraction of sunlight incident on the Earth that is reflected back to space) as a function of the liquid water content in clouds. The light blue lines indicate the range of albedos that can occur for a given liquid-water path, depending on other factors such as the solar zenith angle and the type of ground cover (e.g., bright snow or dark soil).

Using a different approach, we studied the importance of the snow albedo feedback effects (Cess et al., 1991). In this study we compared our results to those from many different climate modeling groups. We found that there was little agreement as to the strength of this feedback because of subtle interactions between the snow cover and clouds and because of other changes in surface processes induced by changes in snow cover.

An important aspect of our work in this area is that it often involves collaboration with university scientists and students. For example, the study of snow albedo feedback was part of a much larger project known as Feedback Analysis for GCM Intercomparison and Observation (FANGIO) involving more than a dozen research groups worldwide. Our contribution to this project was itself a collaborative effort involving our collaborators in the University of California (UC) Institutional Collaborative Research (INCOR) program at Scripps Institution of Oceanography. This INCOR project supported a graduate student who participated in all aspects of this study.

Transport of Heat into the Deep Ocean

The transport of heat into the deep ocean plays an important role in setting the pace of climatic changes, especially how rapidly climate is projected to change in the 21st century. We have initiated two studies related to the representation of heat uptake in oceanic GCMs.

The first study uses an oceanic GCM developed by J. M. Oberhuber of the Max Planck Institute (Oberhuber, 1992a,b). This model uses density as a vertical coordinate and thus allows a more accurate representation of the oceanic transport processes that occur mainly along constant-density surfaces. Figure 4 shows the model-simulated representation of oceanic temperature. A comparison of simulations of global warming by various coupled oceanic-atmospheric models shows that Oberhuber's model responds relatively quickly to climate forcing induced by a doubled carbon dioxide concentration (Covey, 1991). Presumably the model responds quickly because it transports heat into the deep oceans less rapidly than other models, thus confining the heat primarily to the upper layers of the oceans.

This study employs a novel approach to formulating the ocean's exchanges of heat with the atmosphere in order to emulate the evolution of the atmosphere in the course of greenhouse warming. This formulation of the ocean's upper boundary condition allows oceanic models to be tested without computer-intensive coupling to full atmospheric GCMs. Preliminary analysis of the results shows that sea-surface temperatures (SSTs) increase rapidly in this experiment, just as they do in the coupled oceanic-atmospheric simulation using Oberhuber's oceanic model. Analysis of the mechanism of simulated heat transport in the model will better characterize the uncertainty in projections of greenhouse warming due to gaps in knowledge about the oceans.

Our second study involves ocean transport of a passive carbon (^{14}C) tracer. Through a subcontract to the Lamont-Doherty Geological Observatory (LDGO), we are developing a data set of oceanic geochemical tracers that can be used to test oceanic models. The observational data set includes information on the excess ^{14}C (i.e., above the cosmic-ray-produced background) deposited in the ocean following its creation as a result of atmospheric nuclear testing in the late 1950s and early 1960s. We plan to simulate oceanic uptake of excess ^{14}C and then compare the simulation with the data set. This comparison will test the oceanic GCM's ability to transport ^{14}C, as well as any other tracer, including heat and carbon dioxide into the oceans. This project will form

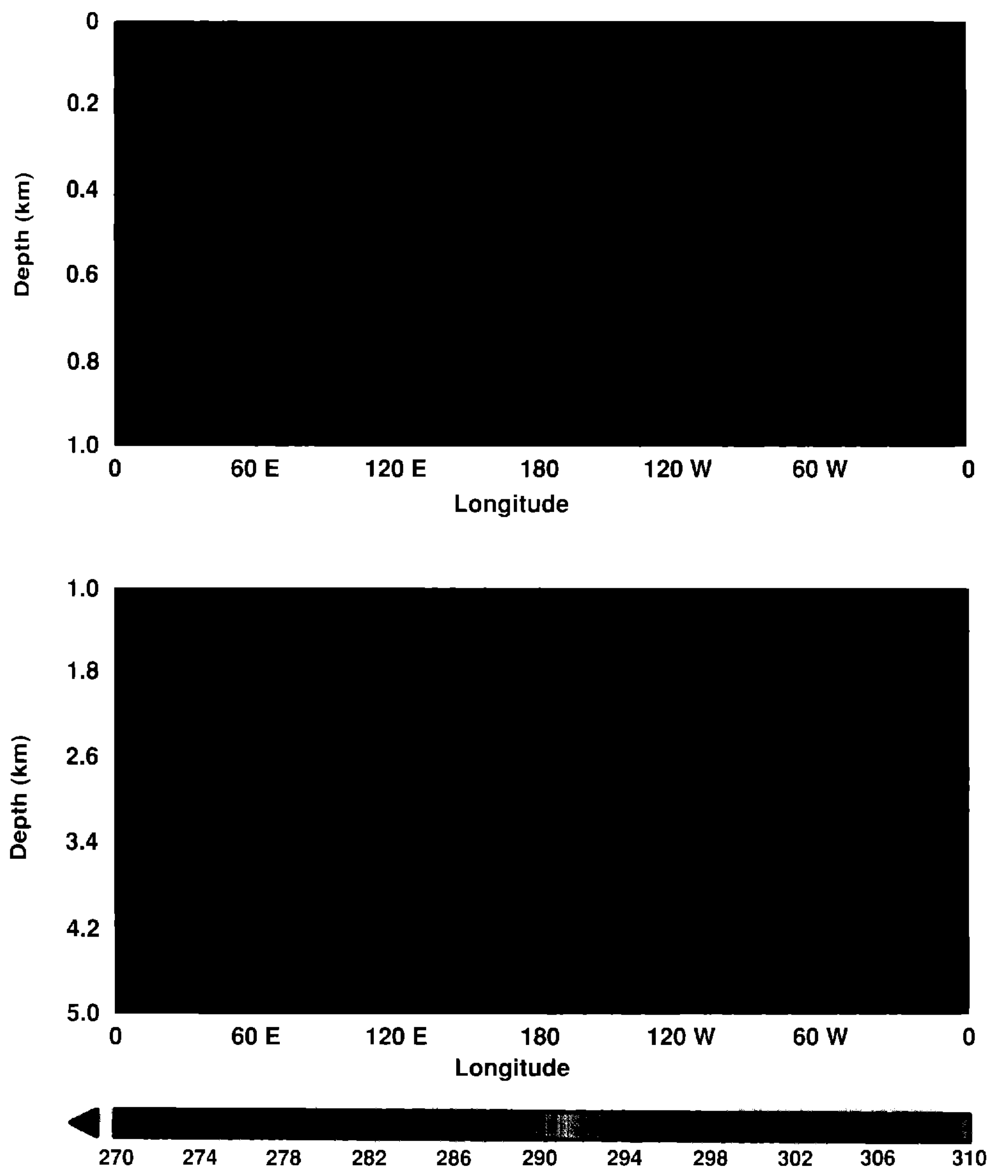

Figure 4. Equatorial zonal section of ocean potential temperature (K) for December as simulated by the isopycnal oceanic general circulation model. The strong variation of temperature through the upper 1 km of the ocean **(a)** contrasts with the rather uniform temperature found in layers below 1 km **(b)**. This model is currently being used to study the uptake of a ^{14}C tracer.

one part of a comparison of carbon-cycle simulations in various types of oceanic GCMs. We will compare ^{14}C transports using both Oberhuber's oceanic GCM and the GFDL's Modular Ocean Model being implemented for the CHAMMP program.

Application Studies

Although our present focus is primarily on model development and verification, we are also performing model application studies to better understand the phenomena that affect the climate and lead to its variability. Particular attention is being devoted to the effects of aerosols on climate (see the "Tropospheric Chemistry and Climate Change" article for a discussion on the effects of sulfate aerosols from human activities).

Global Effects of the El Chichón Volcanic Eruption

Volcanic eruptions are a significant source of natural sulfur aerosols in the stratosphere. Such injections may have caused some of the short-term (<10 yr) global cooling episodes evident in the historical climate record. To quantitate the effects of volcanic aerosols on temperature, we are studying the relationship of the April 1983 El Chichón volcanic eruption in Mexico to the changes in temperature and precipitation of the following year. To isolate the climatic effects of the volcanic aerosol from the effects of the 1982–83 El Niño's intense warming of the eastern tropical Pacific Ocean, we are running a series of experiments with a modified version of the NCAR CCM1.

In one experiment, we imposed the observed SSTs (which included the warming effects of the El Niño) for December 1982 through December 1983, and we prescribed the observed time-varying mass concentration and optical properties of the volcanic aerosols. Results of this experiment are being compared with the results of two other experiments: in one, climatological SSTs (which did not include El Niño events) are prescribed; in the other calculation, the El Chichón aerosol is removed. For each experiment, several realizations (i.e., runs with slightly different initial conditions) have been generated to address problems associated with climatic "noise" and to assess the statistical significance of the results. This work is currently in progress, and we expect our analyses to lead to a better understanding of the historically observed temperature changes that seem to be associated with explosive volcanic eruptions.

Engineering the Climate

We are also examining the potential for planned and inadvertent climate modification. With our sponsorship, scientists at LDGO, in cooperation with the Oak Ridge National Laboratory (ORNL), examined the proposed use of iron to fertilize the ocean and enhance biological removal of carbon dioxide from the atmosphere. It was found that, although some removal of carbon from the atmosphere might be possible, the potential influence was much less than has been suggested.

Similarly, we reviewed the potential for "geoengineering" away the greenhouse-induced climate change by using aerosols, balloons, or satellites to reflect away a compensating amount of solar radiation (MacCracken, 1991). We found that even if society wanted to assume control of the climate, the least expensive schemes would have the most climatic side effects. For example, injection of sulfur aerosols into the stratosphere would result in ozone layer modification. At the other extreme, the schemes having the least side effects would require the largest up-front capital expenses. For example, a mirror positioned at the first Earth-Sun Lagrange point (1.5×10^6 km from the Earth) would likely require establishment of a colony on the Moon to build the mirror (Early, 1989).

Program Management and Outreach for DOE

Since 1978, we have provided advice and assistance in support of DOE's Carbon Dioxide Research Program. Over the past several years, this has included organization and leadership of the science element of the CHAMMP program, leadership in preparation of special reports in support of the National Energy Strategy (NES) and the U.S./U.S.S.R. environmental agreement, and participation in activities to broaden university-laboratory collaboration in research activities.

As initial organizers of the CHAMMP program, we convened an interlaboratory committee to help draft a plan for using MPC architectures for climate modeling. After review by the scientific community, the plan was issued in early 1991, and DOE sought proposals to advance the science elements of the plan. With the review of the proposals and selection of the awards completed, our contribution has moved to organization of the CHAMMP Science Team; the first meeting of which was convened in March 1992.

In support of the NES, we led the DOE Multi-Laboratory Climate Change Committee (MLCCC) in authoring *Energy and Climate Change* (MLCCC, 1990), which provided a perspective for the NES on what is known and not known about the greenhouse effect and future climatic change. An updated report on uncertainties was later provided in support of DOE consideration of U.S. policy options (MacCracken, 1991). Internationally, we led U.S. participation in preparing the joint U.S./U.S.S.R. report *Prospects for Future Climate* (MacCracken et al., 1990), which sought to reconcile U.S. modeling results with the paleoclimatic perspective used by Soviet scientists in projecting future climatic change.

We also provide several interfaces between university and laboratory communities. We serve as the main CHAMMP contact with the Climate System Modeling Project of the University Corporation for Atmospheric Research, which has developed several projects that are examining questions related to building a climate system model. With scientists at several UC campuses and the Los Alamos National Laboratory, we are engaged in a collaborative project to develop a coupled atmospheric-oceanic model. Supported in part by the INCOR program, this project involves scientists from the UC Davis, Los Angeles, Irvine, and Santa Cruz campuses as well as from the Scripps Institution of Oceanography at UC San Diego.

Science Education

With DOE support, we are engaged in a major effort to develop, test, and disseminate a grades K–12 curriculum that focuses on the issue of global warming. The unique aspects of this project are (1) a multidisciplinary focus (that is, the project not only focuses on scientific aspects, but also on social sciences, language, and other aspects), (2) a vertical coordination across grade levels with increasing depth as the students progress through it, and (3) a curriculum that is developed and structured by the teachers. Over the last three years, we have involved high-school, middle-school, and most recently, elementary-school teachers in this multiyear curriculum development effort.

The teachers spend the first summer in intensive discussions with scientists in the field to familiarize themselves with the issue of greenhouse-induced climate change and to provide a basis for developing the initial outline and curriculum. This is an extremely challenging task because the middle- and high-school teachers are usually specialized and are not used to developing a consistent framework across disciplines. Our experience is that most of these teachers enjoy the opportunity to break free of the traditional structure. During the following school year, the teachers test the initial curriculum, refine materials and approaches, and develop new ideas and projects. The elementary-school curriculum is at this stage.

The teachers spend the second summer refining the curriculum by participating in a more extensive review for accuracy and completeness. The teachers also test the curriculum in intense summer workshops with students (Figure 5). In the case of the high-school curriculum, one workshop during the summer involved a combined group of U.S. and (then) Soviet students, a particularly interesting experience for all. The middle-school curriculum is moving into this stage.

The third summer is devoted to teacher workshops in which the teachers who developed the curriculum instruct other teachers on the use of the materials. The high-school curriculum is at this stage. The reception to the approach that all teachers learn about all disciplinary aspects of the curriculum has been very enthusiastic. Our emphasis on training in coming years will be on developing an ever-expanding set of workshop teachers who can more widely disseminate the materials.

Figure 5 As part of the Global Climate Change Curriculum Program, teachers are developing lesson plans and experiments for use in the classroom.

Group Members

The work described in this article was performed by, or under the auspices of, the Climate and Climate Change Group. Scientists involved include Michael C. MacCracken (Group Leader), James R. Albritton, John J. Ambrosiano, Michael C. Axelrod, John H. Bolstad, Curt C. Covey, William P. Dannevik, M. Dolores Doyle, Philip B. Duffy, Donald E. Eliason, Hugh W. Ellsaesser, Peter G. Eltgroth, James R. Kercher, Michael G. McCoy, Art A. Mirin, Manuel Perry, Richard Procassini, Patrick Rouvillois, Dan E. Shumaker, Karl E. Taylor, Michael F. Wehner, and Conrad A. Wilgus. In addition, Joyce E. Penner is responsible for the biogeochemical cycling component of the Earth Systems Modeling project.

The California teachers involved in the Global Climate Change Curriculum Program have included Steve Armstrong (San Ramon), Karen Borowski (Walnut Creek), Carol Caffee (San Francisco), Stephen Dolgin (Oakland), Jeff Hale (Livermore), Kirk Lawrence (Castro Valley), Judy McCurdy (San Ramon), Donna Montague (San Ramon), Carol Mortensen (San Ramon), Bill Pence (San Ramon), Roberta Rankin (Castro Valley), Edel Romay (Oakland), and Robert Schmidt (San Ramon).

We are also participating with a number of researchers from other laboratories, universities, and institutes whose work may not be fully reported here. Appendix B provides a brief summary of these interactions.

Sponsoring Organizations

This work has been supported by several sponsors. They are the Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division; the LLNL Laboratory Directed Research and Development program; and Battelle Pacific Northwest Laboratory.

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ection 3

Numerical Simulation of a Fire-Induced Storm

We simulated the atmospheric dispersion of smoke from an August 1988 planned forest fire in Battersby Township, Ontario, Canada and compared our results with observational data from the Canadian Forestry Service. At the time of the fire, the local atmospheric conditions were favorable for thunderstorm development. Consequently, the fire triggered a succession of convective storm cells that matured as they drifted downwind. This simulation shows the location of the fire (orange) and the smoke plume (gray), in addition to the rain (blue), snow (white), and graupel and hail (red) produced from the line of storm cells. The image, representing a view from the southwest, is a graphical rendering of numerical fields at 838,201 grid points covering a domain 36 km long, 18 km wide, and 12 km tall. The simulation was performed on a Cray-2 computer as a verification test for our OCTET Plume, Storm, and Mesoscale Simulation System.

Appendix A. Staff of the Atmospheric and Geophysical Sciences Program

Contents

G-Division Management

Michael C. MacCracken
Division Leader, and Group Leader for Climate and Climate Change Group, Ph.D., U. Calif., Davis/Livermore, Applied science

Mike has been Division Leader of the Atmospheric and Geophysical Sciences Division since 1987. His research focuses on the study of climate change, with interests including greenhouse-gas–induced change; paleoclimate variations; and changes induced by volcanic aerosols, soot, and nuclear smoke.

Marvin H. Dickerson
Deputy Division Leader, and Group Leader for Cloud Modeling and Experiment Support Group, Ph.D., Florida State U., Meteorology

Marv has been Deputy Division Leader of the Atmospheric and Geophysical Sciences Division since 1987. His research interests include cloud modeling and experiment support. Experiment support in this context is the development of techniques and capabilities used to provide models with data derived from field observations.

Scientific and Engineering Staff*

Rosemary O. Abriam
Computer Scientist,[1] B.S., Calif. State U., Hayward, Computer science, Biology

Rosemary is interested in user interface issues and in artificial intelligence, specifically expert systems. She is a graduate student at Stanford University.

James R. Albritton
Scientist, Ph.D., Yale U., Applied science

Jim is studying the atmospheric hydrological cycle as it regulates the planetary energy budget through radiative coupling. He is interested in experimental

*Numbered footnotes indicate the organizational affiliation of AGS staff members whose affiliation is other than G-Division. The list of affiliations is included at the end of Appendix A.

design and simulation as a means of model validation and is lead scientist in implementing the one-dimensional version of the physics modules of the UCLA atmospheric GCM.

John J. Ambrosiano
Scientist,[2] Ph.D., College of William and Mary, Plasma physics

John is a computational physicist whose areas of interest include algorithms for fluid flow, electromagnetics, computer science, and model design for complex interacting systems. He is developing a computational framework for the Earth Systems Model. He is also assisting in the development of vegetation models for global-scale simulations.

Cynthia S. Atherton
Scientist, M.S., MIT, Atmospheric sciences

Cyndi is interested in computer modeling of atmospheric chemistry and physics on regional-to-global scales. She studies the atmospheric chemistry of the natural and polluted troposphere, particularly tropospheric ozone. She is pursuing her Ph.D. at the University of California, Davis.

Michael C. Axelrod
Electronics Engineer,[3] M.S., New York U., Applied mathematics

Mike is interested in the data analysis of global environmental and biological variables and in simulating the effects of global climate change. He is currently working on developing steady-state models of vegetation response to global climate change.

Ronald L. Baskett
Scientist,[4] M.S., U. Calif., Davis, Atmospheric sciences

Ron is interested in dispersion models on local and regional scales as applied to emergency response and air-quality problems. He also works on integrating data from meteorological measurement systems into ARAC models and evaluating the MATHEW/ADPIC models against tracer experiments.

Daniel J. Bergmann
Computer Scientist,[1] M.S., U. Calif., Davis, Computer science

Dan is working on developing and applying models for predicting the dispersion and chemistry of aerosols in the atmosphere. His interests include numerical methods, applied mathematics, massively parallel computing, and scientific visualization.

John H. Bolstad
Scientist,[2] Ph.D., Stanford U., Numerical analysis

John is interested in computational fluid dynamics, including the areas of adaptive mesh refinement, multigrid continuation methods, and the computation of multiple solutions of Taylor-Couette flow. He is working on transferring an oceanic GCM to massively parallel computers.

Diane F. Bonner
Computer Scientist,[1] B.S., State U. New York, Albany, Mathematics

Diane is interested in user interface design and VAX software engineering tools.

William J. Bosl
Computer Scientist,[1] Ph.D., U. Illinois, Urbana/Champaign, Atmospheric sciences

Bill is interested in applying computational physics techniques to atmospheric science problems of national and international interest.

James S. Boyle
Scientist, Ph.D., State U. New York, Stony Brook, Atmospheric sciences

Jim is interested in developing diagnostics to investigate the dynamics of models and observations. He is also interested in satellite remote sensing.

Michael M. Bradley
Scientist, Ph.D., U. Illinois, Urbana/Champaign, Atmospheric sciences

Mike is interested in simulating cloud morphology, particularly the morphology of cumulonimbus clouds. He is also interested in using data to validate cloud models that include microphysics.

Jonathan C. Brown
Computer Scientist,[5] B.S., Western Washington U., Computer science

Jonathan's research interests include parallel and distributed computing, and graphical user interfaces. He is working on parallel and distributed processing for atmospheric modeling.

Edward Bush
Computer Technician,[4] B.B.A., Pacific Lutheran U., Business administration

Ed is interested in how meteorological measuring devices communicate with computer components. He assists in maintaining ARAC's DEC VMS environment.

Richard T. Cederwall
Scientist, M.S., San Jose State U., Meteorology

Ric is interested in modeling turbulence in the planetary boundary layer and is pursuing this topic in his dissertation research at Stanford University. He is also interested in atmospheric transport and diffusion phenomena on local-to-regional scales.

Bor Chan
Computer Scientist,[5] M.S., San Jose State U., Computer science

Bor is working on parallel processing for atmospheric modeling. His research interests include parallel programming languages and automatic parallelization.

Stevens T. Chan
Scientist, Ph.D., U. Calif., Davis, Mechanical engineering

Stevens' recent research activities include the development and application of two- and three-dimensional computer programs for modeling incompressible flows, mesoscale atmospheric flows, and the atmospheric dispersion of heavy gases.

D. Carol Chapman
Computer Scientist,[1] B.S., Calif. State U., Hayward, Computer science

Carol is interested in computer-graphic standards; specifically GKS, COM, IGES/PDES, and geographical information systems. She is also interested in the X Window System and in promoting the use of software engineering methodologies.

Keith T. Chiles
Computer Technician,[1] M.B.A., U. Phoenix, Business administration

Keith is interested in departmental computer system management, in particular the organizational development of departmental computing environments.

Hung-Neng S. Chin
Postdoctoral Scientist, Ph.D., U. Illinois, Urbana/Champaign, Atmospheric sciences

Steve is interested in the mesoscale aspects of convective storm dynamics, especially the representation of the dynamic and radiative effects of clouds in GCMs and the coupling of cloud- and global-scale motions. His interests also include the regional impact of global climate change

Wanda Chiu
Computer Scientist,[1] M.E., Cornell U., Computer science

Wanda is interested in the design and implementation of application software for distributed computer environments. She is also interested in software methodology.

Woo-Kap Choi
Postdoctoral Scientist, Ph.D., U. Washington, Atmospheric sciences

Woo-Kap is interested in the dynamical processes that control the transport of constituents in the atmosphere, in particular the stratosphere and above.

Catherine C. Chuang
Postdoctoral Scientist, Ph.D., U. Illinois, Urbana/Champaign, Atmospheric sciences

Cathy is interested in the microphysics of clouds and precipitation, including the parameterization of these processes in mesoscale and global models, and in the effects of pollutants on microphysics and climate. She is also interested in atmospheric electricity.

Peter S. Connell
Scientist, Ph.D., U. Calif., Berkeley, Chemistry

Peter is interested in the trace composition and photochemistry of the troposphere and stratosphere and in the related areas of gas-phase kinetics and spectroscopy. He has modeled the effects of chlorofluorocarbons on the atmosphere and is involved with the Upper Atmosphere Research Satellite program.

Stephen P. Cooper
Computer Scientist,[1] B.S., Purdue U., Computer science

Steve is interested in data communications and networking as applied to distributed computer applications.

Lisa C. Corsetti
Computer Scientist,[1] M.S., State U. New York, Albany, Atmospheric sciences

Lisa is interested in climate modeling and climate model analysis.

Curtis C. Covey
Scientist, Ph.D., U. Calif., Los Angeles, Physics

Curt is interested in the oceans' role in climatic change. He is preparing to use an oceanic GCM to examine factors controlling the rate of global warming in response to human-produced greenhouse gases.

J. Daryl Crew
Computer Scientist,[1] M.S., Calif. State U., Hayward, Mathematics

Daryl is interested in developing application software that utilizes applied mathematics and computer graphics.

William P. Dannevik
Scientist,[2] Ph.D., St. Louis U., Meteorology

Bill is interested in the theoretical and computational aspects of turbulent-flow phenomena, in particular the formulation and testing of turbulence closure models. He is applying massively parallel computing resources to problems in computational fluid dynamics and the chaotic dynamics of large-scale coupled geophysical flow systems.

Clyde G. Dease
Scientist,[3] Ph.D., George Washington U., Physics

Clyde works with the simulation data sets generated by the participants of the Atmospheric Model Intercomparison Project. He extracts data from their files, inspects the contents graphically, and stores the data sets in the PCMDI standard Data Retrieval Storage format.

Charlayne L. Deming
Computer Technician[4]

Charlayne works on all phases of system and network management for UNIX/DOS/Macintosh-based systems.

Jane E. Dignon
Postdoctoral Scientist, Ph.D., State U. New York, Stony Brook, Mechanical engineering

Jane is interested in modeling atmospheric chemical processes. Her research focuses on developing global trace-gas emissions inventories from natural and anthropogenic sources and studying the effects these emissions have on ambient trace-gas concentrations and climate.

M. Dolores Doyle
Program Manager,[6] Global Climate Change Curriculum Program

Dolores has been the Program Manager for the Global Climate Change Curriculum Program since 1990. Her interest is in working with K–12 teachers for the continued development of global climate change curriculum and in disseminating the curriculum materials to teachers through nationwide workshops.

Robert S. Drach
Computer Scientist,[1] M.S., Ohio U., Mathematics, Industrial engineering

Bob is interested in scientific database development, artificial intelligence, scientific programming, and applied mathematics.

Philip B. Duffy
Scientist,[7] Ph.D., Stanford U., Astronomy

Phil is interested in global climate change, ocean modeling, and remote sensing. He is working on the use of oceanic GCMs for tracer, biogeochemical, and dynamical studies.

Harold E. Eddleman
Computer Scientist,[1] B.S., U.S. Naval Postgraduate School, San Diego, Physics, Electronic engineering

Hal provides computational support for the Atmospheric Microphysics and Chemistry Group's studies of aerosol transport and climate effects using GRANTOUR and the CCM1/GRANTOUR coupled model.

Leslie L. Edwards
Scientist, M.A., U. Oregon, Mathematics

Les is interested in numerical solutions of physics problems such as compressible fluid dynamics, reactor safety, waste disposal, and cloud microphysics. His current work is in the areas of atmospheric fallout phenomenology, pollutant transport, and predictor/corrector integration of measurements with models.

Donald E. Eliason
Postdoctoral Scientist,[8] Ph.D., Texas A&M, Oceanography

Don is interested in ocean circulation modeling and in oceanic biogeochemical cycles.

James S. Ellis
Scientist, Ph.D., Colorado State U., Atmospheric sciences

Jim is interested in satellite remote sensing of the Earth-atmosphere system and in the development and application of atmospheric dispersion models.

K. Patrick Ellis
Computer Technician

Pat has been responsible for meteorological tower maintenance for both the ARAC center and the Atmospheric Studies in Complex Terrain program. He participates in performing experiments and recording data for use in modeling studies.

Peter G. Eltgroth
Scientist,[9] Ph.D., Harvard U., Physics

Peter is interested in developing computational physics models for understanding the Earth system, especially systems interaction and subscale phenomena.

Donald L. Ermak
Group Leader, Atmospheric Flow and Dispersion Modeling Group, Ph.D., U. Calif., Davis, Applied physics

Don is interested in atmospheric dispersion modeling within the boundary layer with an emphasis on the dispersion of denser-than-air releases. He is currently extending a trace-gas, advection-diffusion model to include dense-gas dispersion over complex terrain and is developing Monte Carlo statistical techniques to simulate atmospheric turbulence.

Kathleen M. Fischer
Computer Scientist,[1] B.S., U. Calif., Davis, Computer science

Kathleen is interested in computer graphics and user interfaces.

Connee S. Foster
Scientist, M.S., Oregon State U., Meteorology

Connee is interested in boundary-layer meteorology and atmospheric dispersion modeling with an emphasis on application to emergency response and preparedness.

Kevin T. Foster
Scientist, M.S., U. Calif., Davis, Meteorology

Kevin is interested in modeling of the boundary layer, especially as applied to operational emergency response and the regional transport and diffusion of atmospheric pollutants.

Robert P. Freis
Computer Scientist,[1] M.S., U. Calif., Berkeley, Engineering science

Bob is interested in several categories of computer science and computational physics: numerical modeling of physical processes, numerical analysis, user interface, numerical solutions of PDEs and ODEs, graphics, and visualization.

Donald A. Garka
Engineering Technician,[3] B.S., Devry Inst. Tech., Electronics engineering

Don is interested in computer system management, network management, and database systems.

W. Lawrence Gates
Director, Program for Climate Model Diagnosis and Intercomparison, Ph.D., MIT, Meteorology

Larry is interested in a broad range of subjects in atmospheric dynamics and numerical modeling, including dynamics of climate; ocean-atmosphere modeling; the climatic effects of increased greenhouse gases; and climate model validation, diagnosis, and intercomparison.

Raymond D. Gentry
Scientist,[10] B.S., Midwestern State U., Texas, Physics, Mathematics

Raymond is interested in computer simulations of physical systems, particularly in the area of atmospheric science. He also enjoys investigating numerical analysis as applied to these models.

Yolanda G. Glaeser
Computer Technician,[4] A.A., Ohlone C., Fashion merchandising

Yolanda is interested in effective management of data and communications for emergency response and in efficient procedures for running models in support of complex assessment studies.

Peter J. Gleckler
Scientist, M.S., U. Calif., Davis, Mechanical engineering

Peter is interested in ocean-atmosphere energy exchange and its relevance to climate variability. He is pursuing his Ph.D. at the University of California, Davis.

Benjamin C. Graboske
Scientific Associate, U. Calif., Berkeley, Physics

Ben is interested in modeling global-scale transport phenomena to test the capabilities of global models to treat various trace species components. He has studied various aspects of the nitrogen cycle and the production and transport of ^{7}Be. Ben is an undergraduate in the Physics Department at the University of California, Berkeley.

Keith E. Grant
Scientist, Ph.D., U. Calif., Davis, Applied science

Keith is interested in radiation transport, especially the modeling and parameterization of radiative physics and photochemistry. He is also interested in atmospheric data analysis and display.

Philip M. Gresho
Scientist, Ph.D., U. Illinois, Urbana/Champaign, Chemical engineering

Phil is interested in numerical methods, in particular finite-element methods for fluid mechanics. His research focuses on the physics, mathematics, and numerical simulation of viscous incompressible flow. He is also interested in buoyancy-coupled flows.

Allen S. Grossman
Scientist, Ph.D., Indiana U., Bloomington, Astrophysics

Allen is interested in theoretical modeling of radiation transport in the Earth's atmosphere, in particular the interaction between the radiation field and the chemical processes that determine the abundances of the important elements in the atmosphere. He is also interested in modeling the energy sources that determine the internal structure and evolution of the giant planets Jupiter and Saturn.

Stanley L. Grotch
Scientist, Ph.D., MIT, Chemical engineering

Stan is interested in developing and applying statistics and graphics to meteorological data with an emphasis on greenhouse-gas–induced climate change.

Paul H. Gudiksen
Group Leader, Model Applications and Nuclear Effects Group, Ph.D., U. Washington, Chemistry

Paul is interested in nuclear and toxic-chemical emergency response modeling. His research focuses on boundary-layer modeling in complex terrain, analysis of meteorological and tracer measurements, and nuclear accident assessments.

Ted F. Harvey
Scientist, Ph.D., U. Calif., Davis, Physics

Ted's expertise is in local and global fallout and rainout. He is interested in the integration of measurements into emergency response models; optimization of sampling networks; nuclide transport from the reactor core to and through the environment and on to humans; nuclear waste management; numerical model inversion; probabilistic risk analysis; and stochastic modeling.

Anthony T. Hoang
Computer Technician,[4] San Jose State U., Computer science

Tony is interested in VAX- and UNIX-based system management and administration. He is an undergraduate at San Jose State University.

John K. Hobson
Computer Scientist,[1] M.S., U. Calif., Berkeley, Mathematics

John is interested in numerical analysis, fluid dynamics, and computing environments.

Susan Kemball-Cook
Scientific Associate, B.A., Yale U., Physics

Susan is interested in modeling the physical processes of radiative transport. She is pursuing her M.S. at San Francisco State University.

James R. Kercher
Scientist,[11] Ph.D., Cornell U., Theoretical physics

Jim is interested in the mathematical analysis of ecosystem dynamics. He is currently developing models of the global terrestrial ecosystem for coupling with models of atmospheric circulation, atmospheric chemistry, and ocean processes.

Jinwon Kim
Postdoctoral Scientist, Ph.D., Oregon State U., Physics

Jinwon is interested in modeling gravity wave phenomena and boundary-layer physical processes, in particular turbulence and air–ground-surface interactions. He is presently working on interfacing a regional model with a GCM to study regional climate effects in California due to general climate changes brought on by a doubling of the CO_2 concentration.

Douglas E. Kinnison
Scientist, Ph.D., U. Calif., Berkeley, Chemistry

Doug is interested in global atmospheric chemical and physical processes. His research focuses on trace-gas emissions from natural and anthropogenic sources, including their effect on atmospheric trace-gas concentrations (e.g., stratospheric ozone distribution) and climate. In addition, he is studying the effects of NO_x emissions from proposed fleets of high-speed civil transport aircraft on global ozone distributions.

Thomas A. Kuczmarski
Computer Scientist,[1] M.S., U. Wisconsin, Madison, Computer science

Tom has a broad background in computer science, including operating system modifications and compiler construction. His current interests include the design and implementation of graphical user interfaces using C and X Windows/Motif technology in a UNIX environment.

Rolf Lange
Scientist, Ph.D., U. Calif., Davis, Atmospheric sciences

Rolf is interested in atmospheric fluid dynamics, specifically turbulent diffusion of atmospheric pollutants. His emphasis is on numerical modeling of the transport and diffusion of pollutants in the planetary boundary layer.

Leonard A. Lawson
Computer Scientist,[1] A.B., Calif. State U., Chico, Mathematics

Len is interested in numerical methods with respect to atmospheric transport and diffusion models.

Bryan S. Lawver
Scientist,[3] Ph.D., U. Calif., Davis, Electronics engineering, Computer science

Bryan is interested in real-time unattended environmental assessments using advanced dispersion models on a dedicated workstation that can acquire its own sensor data

Denise A. Leddon
Computer Scientist,[4] B.S., San Francisco State U., Computer science

Denise analyzes, designs, and implements software to support ARAC computer systems.

Robert L. Lee
Scientist, Ph.D., U. Calif., San Diego, Engineering physics

Bob is interested in developing and applying numerical models, particularly those based on the finite-element method, to the atmospheric boundary layer. His activities include exploring the use of a mesoscale model for regional climate simulations and modeling higher order turbulence with application to flow and dispersion of pollutants around buildings.

John M. Leone, Jr.
Scientist, Ph.D., Iowa State U., Meteorology

John is interested in the numerical simulation of incompressible fluid flows with an emphasis on mesoscale meteorological flows. He has concentrated his efforts on applying finite-element methods to the simulation of planetary boundary-layer flows driven by interactions between the atmosphere and local complex topography.

Ambrosio R. Licuanan
Computer Technician,[1] A.A., Ohlone C., Computer science

Beb is interested in UNIX Local Area Network management, autotasking of large application codes, and interactive graphics analysis tools.

Rose C. McCallen
Scientist,[1,2] M.S., U. Calif., Davis, Mechanical engineering

Rose's modeling interests are in the area of Large Eddy Simulation (LES) using the finite-element methodology as a mathematical framework for solving the Navier-Stokes equations. Her Ph.D. research involves applying LES to simulating flows around buildings.

John E. Mak
Postdoctoral Scientist,[13] Ph.D., U. Calif., San Diego, Atmospheric chemistry

John is interested in using isotopes to help constrain both dynamical and chemical processes in the atmosphere. His appointment is held jointly with the LLNL Center for Accelerator Mass Spectrometry, which allows him to pursue the experimental aspects of isotopic analysis of trace species.

Mary Ann Mansigh
Computer Scientist,[1] B.S., U. Minnesota, Duluth, Mathematics, Chemistry

Mary Ann is interested in the prototyping and development of software tools for efficient computer model analyses. She is also interested in chemical-radiative-transport modeling.

Arthur A. Mirin
Group Leader,[5] Ph.D., U. Calif., Berkeley, Mathematics, Computational physics

Art is interested in developing advanced global climate models for high performance computing systems.

Robert L. Mobley
Computer Scientist,[1] B.S., Northeast Missouri State U., Mathematics, Physics

Bob is interested in fluid dynamical modeling, networking, and parallel computing. He is also interested in graphics and methods for dealing with very large databases.

Charles R. Molenkamp
Scientist, Ph.D., U. Arizona, Meteorology

Chuck is interested in cloud physics, cloud modeling, parameterization of microphysics and scavenging microphysics, and precipitation scavenging. He is also interested in the interactions between clouds and radiation. His numerical modeling studies include the simulation of fog and cloud formation in mesoscale regions.

R. Miki Moore
Computer Scientist,[1] M.S., U. Calif., Berkeley, Computer science; M.A., U. Calif., Berkeley, Geology

Miki is interested in the analysis, design, and implementation of computer modeling systems on UNIX-based Sun workstations.

John S. Nasstrom
Scientist,[4] M.S., U. Calif., Davis, Atmospheric sciences

John is interested in dispersion modeling and boundary layer meteorology and their application in real-time emergency response systems. He is pursuing advanced boundary-layer dispersion methods in his Ph.D. studies at the University of California, Davis.

Charles J. O'Connor
Computer Scientist,[1] M.S., Calif. State U., Hayward, Computer science

Charlie is interested in developing and maintaining high-speed, three-dimensional atmospheric chemical models on vector and parallel computers.

Kenneth O. Patten
Postdoctoral Scientist,[13] Ph.D., U. Calif., Berkeley, Physical chemistry

Ken is interested in the photochemistry of the atmosphere, in reactions and interactions of excited state species, and in parameterization of data for computer simulation.

Joyce E. Penner
Group Leader, Atmospheric Microphysics and Chemistry Group. Ph.D., Harvard U., Applied mathematics

Joyce is interested in modeling of global tropospheric chemistry and its interactions with climate. Her current focus is on modeling tropospheric oxidant levels and aerosols. She is developing models that provide the capability to simulate aerosol concentrations, tropospheric ozone, and aerosol-cloud interactions.

Manuel Perry
Director,[6] LLNL Education Program, Ph.D., USC, Public administration

Manuel has been involved in educational programs offered by LLNL since the late 1960s. He now leads a group that sponsors and coordinates LLNL educational programs for schools and colleges from kindergarten through graduate school. He was instrumental in implementing the global climate change interdisciplinary curriculum materials.

Linda G. Peters
Scientist,[4] M.S., Colo. School of Mines, Physics

Lin is interested in developing and applying numerical models to simulate the dispersion and deposition of radionuclides. Her current research focuses on probabilistic risk analysis and particle model development.

Thomas J. Phillips
Scientist, Ph.D., U. Wisconsin, Madison, Meteorology

Tom is interested in investigating climate model predictions on seasonal-to-decadal time scales. He has recently focused on simulations that are driven by satellite-derived observations of surface temperatures over the oceans and sea ice.

Brenda M. Pobanz
Scientist,[4] M.S., U. Wyoming, Atmospheric sciences

Brenda is interested in applying atmospheric models, both regional and hemispheric, that simulate the dispersion and deposition patterns of hazardous atmospheric releases, and in verifying the results using measurements and satellite data.

Gerald L. Potter
Deputy Director, Program for Climate Model Diagnosis and Intercomparison, Ph.D., U. Calif., Los Angeles, Geography

Jerry is interested in climatic feedback mechanisms, regional climate change, cloud radiative forcing, and the general climatic effects of greenhouse warming.

Gregory H. Rau
Scientist,[14] Ph.D., U. Washington, Liminology

Greg is interested in marine nutrient cycling and the effects of iron fertilization on primary productivity. He is studying the relationship between primary productivity and iron deposition.

Leon O. Richardson
Computer Technician,[4] B.S., Loma Linda U., Psychology

Leon is interested in the management of computer networks with an emphasis on hardware integration within a cluster environment.

Howard C. Rodean
Scientist, M.S., Purdue U., Aeronautical engineering; M.S., Southern Methodist U., Nuclear engineering

Howard has contributed to the development of the FEM3A model for gas transport and dispersion, in particular the material phase-change submodel. He has extended this phase-change work to a generalized structure for modeling complex material behavior. He is currently applying the Langevin (random walk) model for turbulent dispersion to the ADPIC model.

Daniel J. Rodriguez
Scientist, M.S., San Jose State U., Meteorology

Dan is interested in numerical modeling techniques for the atmospheric transport and diffusion of trace species on a continental-to-hemispheric scale. His modeling effort focuses on providing a real-time response capability.

J. Alan Ross
Scientific Associate, M.S., U. Idaho, Hydraulic engineering

Alan is interested in computational fluid mechanics with an emphasis on two- and three-dimensional turbulence modeling. He is also interested in color graphics codes. Alan is pursuing his Ph.D. at the University of California, Davis.

Douglas A. Rotman
Scientist, Ph.D., U. Calif., Berkeley, Mechanical engineering

Doug is interested in atmospheric dynamics and the transport of trace chemical species. His research has focused on use of the LLNL two-dimensional chemical-radiative-transport model to study the interaction between advective-diffusional processes and the global distribution of trace chemical species. He is developing a three-dimensional atmospheric-chemistry-transport model for use on massively parallel computers.

Patrick Rouvillois
Visiting Scientist,[15] M.S., Universite de Paris VI, Paris, France, Mathematics

Patrick is interested in climate modeling, in particular ocean modeling. He is working on the conversion of the GFDL Modular Ocean Model to massively parallel computers.

Benjamin D. Santer
Scientist, Ph.D., U. of East Anglia, Norwich, England, Climatology

Ben is interested in the detection of greenhouse-gas–induced climate change in observed data. His research has focused on the statistical aspects of detection, in particular the identification of climate variables that may form useful components of a multivariate greenhouse-gas "fingerprint."

Kristie A. Sasser
Computer Technician[4]

Kristie is interested in network and system management in a UNIX or VMS environment with an emphasis on hardware configurations for the UNIX platform.

Walter W. Schalk, III
Scientist,[4] B.S., Florida State U., Meteorology

Walt is interested in using atmospheric models for real-time assessment of hazardous material accidents with an emphasis on accidents occurring in severe weather (e.g., thunderstorms and hurricanes). He is involved with assessments for Safety Analysis Reports and Environmental Impact Statements. He is also interested in the application of models to other types of particles injected into the atmosphere (e.g., volcanic ash, smoke, and soot) on a regional-to-hemispheric scale.

Sailes Sengupta
Scientist,[3] Ph.D., U. Calif., Berkeley, Statistics

Sailes is interested in the advanced statistical analysis of simulated and observed climate data, in particular the use of principal component analysis and neural networks.

Dan E. Shumaker
Scientist,[5] Ph.D., U. Calif., Davis, Applied science

Dan is working on algorithmic development for conversion of an atmospheric GCM to massively parallel computers. His general interest is in computational physics.

Kenneth M. Skinnell
Computer Technician[1]

Ken is interested in system and network administration. He is currently responsible for PCMDI's Macintosh Appletalk network. He is interested in user interface technology and design and has been involved with the beta testing and evaluation of Macintosh software packages.

Kenneth R. Sperber
Scientist, Ph.D., State U. New York, Stony Brook, Mechanical engineering

Ken is interested in the simulation of interannual variability with coupled ocean-atmosphere global climate models. His research has shown that coupled models can be used to study time-dependent phenomena in addition to climate equilibrium properties.

Mark E. Spruiell
Computer Scientist,[1] B.S., San Jose State U., Computer science

Mark is interested in the design of graphical user interfaces and their implementation in the X Window System. He is also interested in object-oriented systems and methodologies. Mark is currently developing emergency-response applications using OSF/Motif in a UNIX environment.

John L. Stout
Engineer,[16] M.S., Colo. School of Mines, Geological engineering

John is interested in the visual display of simulated data from GCMs. He is developing techniques for computer-generated database queries to browse large data sets for sensitive features of both observed and simulated data.

Thomas J. Sullivan
Director, Atmospheric Release Advisory Capability, Ph.D., U. Calif., Davis, Atmospheric sciences

Tom is interested in applying atmospheric models to real-time consequence assessments of hazardous material accidents; his primary emphasis is on the local-to-regional scale but extends also to the global scale. His interests focus on the integration of evolving computer technologies, databases, and communications with advanced dispersion models to support emergency-response decision processes.

Denise A. Sumikawa
Computer Scientist,[1] M.S., U. Calif., Davis, Computer science

Denise is interested in the human-factor design of graphical user interfaces for scientific applications. Her current assignment involves the design and implementation of user interface applications for the UNIX-based ARAC Site Workstation System using the X Window System and OSF/Motif graphical user interface environment.

John S. Tamaresis
Scientific Associate, B.S., U. Calif., Berkeley, Mechanical engineering

John is interested in atmospheric chemical and physical processes. He is investigating the tropospheric photochemistry of hydrocarbons and their effects on the trace-gas composition of the atmosphere. His modeling efforts focus on the impact of hydrocarbons on global atmospheric chemical cycles. John is pursuing his M.S. in Chemical Engineering at San Jose State University.

Raymond L. Tarp
Computer Scientist,[1] B.A., San Jose State U., Mathematics

Ray is interested in the aesthetics involved in developing computer models for use in scientific research. He focuses on the development of models that can easily accommodate major coding modifications as dictated by possible diverse changes in future scientific direction. He is currently applying his knowledge to design atmospheric models.

Allan G. Taylor
Computer Scientist,[1] M.S., U. Denver, Physics; M.S., So. Oregon College, Mathematics

Allan is interested in a wide range of computational and mathematical methods and their application to physics and the physical sciences. In particular, he is interested in developing and applying algorithms and computational techniques in support of fast-response modeling of atmospheric dispersion.

Karl E. Taylor
Scientist, Ph.D., Yale U., Physics

Karl is interested in a wide range of scientific issues relating to the global climate. His recent research activities have included climate model studies on the effects of clouds on climate and climate change, and the potential importance of sea-ice albedo feedback.

Khai Trinh
Scientist,[4] B.S., San Francisco State U., Computer science

Khai is interested in computer user interface design and programming in the VAX environment. Other related interests include the VAX code management system and relational database design.

David P. Turner
Computer Scientist,[1] B.S., Western Washington U., Mathematics, Computer science

Dave is interested in numerical methods, parallel processing, and graphics.

Charles Veith
Facilities Associate

Chuck provides assistance in supporting emergency response systems.

Phil Vogt
Scientist,[4] B.S., San Jose State U., Meteorology

Phil is interested in the planetary boundary layer and in severe local scale meteorological events.

Hoyt Walker
Computer Scientist,[1] M.S., U. Calif., Davis, Computer science; M.A., San Jose State U., Geography

Hoyt is interested in the relationship between geographic data and atmospheric models as well as computer cartography and geographic information systems. He is pursuing his Ph.D. in Geography at the University of California, Santa Barbara.

John J. Walton
Scientist, Ph.D., U. Kansas, Physics

John is interested in the modeling of global-scale atmospheric transport and removal processes and in the inclusion of chemical reactions in these models.

Michael F. Wehner
Scientist,[2] Ph.D., U. Wisconsin, Madison, Nuclear engineering

Mike is interested in the grid-point-based massively parallel atmospheric GCM. This computer code will be a part of the LLNL Earth System Model.

Jon G. Welch
Electronic Technician,[3] Delta C., Chabot C., Electronic technology

Jon is interested in data communications. He is also interested in trouble-shooting electronic components.

Dean N. Williams
Computer Scientist,[1] M.S., Calif. State U., Chico, Computer science

Dean is interested in the development of visualization capabilities and a window interface for PCMDI's new visualization analysis tool (PCMDI Graphics Version 2.0). He is also maintaining PCMDI Graphics Version 1.0.

Donald J. Wuebbles
Group Leader, Global Radiation, Chemical, and Dynamical Interactions Group, Ph.D., U. Calif., Davis
Atmospheric sciences

Don is interested in interactions of atmospheric chemical, radiative, and dynamical processes; modeling of global atmospheric, chemical, and physical processes; tracer transport in the troposphere and stratosphere; perturbations to the global atmosphere; and changes in atmospheric composition that affect climate.

Administrative Management

Camille A. Vandermeer
Administrator

Jeffrey D. Horne
Facilities Coordinator

Floy L. Worden
Resource Manager

Administrative and Technical Support Staff

Augustin N. Arrivas
SUN Network Support

Michelle A. Baca
Administrative Support for Global Climate Change Curriculum Program

Julie J. Bagorio
Procurement/Property Specialist

Cynthia D. Brandt
Administrative Support Assistant for Program for Climate Model Diagnosis and Intercomparison

Colleen D. Camacho
Administrative Support for Atmospheric Microphysics and Chemistry Group

Denise V. Castro
Administrative Support for Atmospheric Release Advisory Capability Group

Raylene Cooper
Manager for Technical Publications Center

Pamela M. Drumtra
Lead Administrative Support for Division

Maureen F. Duncan
Administrative Support for Model Applications and Nuclear Effects Group

Amy E. Henke
Technical Publications Assistant

Arleen L. Iman
Administrative Support for Division Leader, Deputy Division Leader, and Cloud Modeling and Experiment Support Group

Joanne Klemstein
Administrative Support for Global Climate Change Curriculum Program

Dianna D. Leap
Administrative Support for Global Radiation, Chemical, and Dynamical Interactions Group

Paul S. Mauvais
SUN Network Support

Lori E. McDowell
Administrative Support for Program for Climate Model Diagnosis and Intercomparison

Jennifer L. Miller
Administrative Support Assistant

Marilyn J. Miller
Assistant Resource Manager

Mabel K. Moore
Macintosh Computer Support

Cinda L. Owens
Librarian

Lourdes Placeres
Administrative Support for Atmospheric Flow and Dispersion Modeling, and Climate and Climate Change Groups

Participating Guest Scientists

Julius S. Chang, State U. New York, Albany
Interest: Comparison of satellite observations and model results

Helmut Daniels, Institüt für Wasserbau of the RWTH, Aachen, Federal Republic of Germany
Interest: Code development for numerical methods

Robert G. Ellingson, U. Maryland
Interest: Radiation transport

Hugh W. Ellsaesser, LLNL, retired
Interest: Atmospheric dynamics, climate change

George D. Greenly, International Technology Corp., Irvine, Calif.
Interest: Meteorology

Joseph B. Knox, U. Calif., Davis
Interest: Meteorology

Sonia Kreidenweis-Dandy, Colorado State U.
Interest: Microphysics of aerosols

Cecil E. Leith, LLNL, retired
Interest: Computational hydrodynamics

Erik Naslund, National Defence Research Establishment, Sweden
Interest: Atmospheric dispersion and meteorological modeling

Sheo S. Prasad, Lockheed Missile and Space Corp.
Interest: Comparison of satellite observations and model results

Leonard C. Rosen, San Francisco State U.
Interest: Atmospheric optics and wave propagation

Robert L. Sani, U. Colorado
Interest: Fluid mechanics, chemical engineering, and applied mathematics

Charles S. Shapiro, San Francisco State U.
Interest: Radiological impact of large-scale releases of nuclear materials

Carla Wong, NASA/Ames Research Center
Interest: Climate and environmental studies

Short-term Student Employees and Student Guests

Jeffrey Q. Chambers
Calif. Polytechnic State U., San Luis Obispo, Biochemistry

Delfred Gene
Northern Arizona U., Engineering technology

Royce H. Kam
U. Hawaii at Manoa, Physics, Mathematics

Amit D. Mehta
Rice U., Physics

Cyndi D. Nevison
Stanford U. and National Center for Atmospheric Research, Atmospheric sciences

Milan B. Reichbach
Syracuse U., Physics

Jean Schantz
U. Texas, Austin, Mathematics, Computer science

Marcy Skinnell
U. the Pacific, Computer science

Brad J. Staley
U.S. Naval Academy, Physics

Marlon D. Veal
San Jose State U., Physics

Tiffany Vela
Calif. Polytechnic State U., San Luis Obispo, Computer science

Mytilee Vemuri
U. Calif., Davis, Chemical engineering

Consultants

James F. Barbieri, U.S. Navy
Discipline: Database management

Alfred K. Blackadar, Self-employed
Discipline: Micrometeorology

Wallace S. Broecker, Columbia U.
Discipline: Atmospheric studies and environmental science

Robert D. Cess, State U. New York, Stony Brook
Discipline: Climatic effects of Arctic aerosols and GCM intercomparison

Robert M. Chervin, National Center for Atmospheric Research
Discipline: Computer modeling of atmospheric and oceanic circulation

Ralph J. Cicerone, U. Calif., Irvine
Discipline: Geosciences and atmospheric chemistry

Rudolph J. Engelmann, Self-employed
Discipline: Atmospheric sciences

Sultan Hameed, State U. New York, Stony Brook
Discipline: Atmospheric sciences

Martin I. Hoffert, New York U.
Discipline: Environmental and energy science

James R. Ipser, U. Florida
Discipline: Theoretical astrophysics

Joseph B. Klemp, National Center for Atmospheric Research
Discipline: Fluid mechanics

Steven K. Krueger, U. Utah
Discipline: Atmospheric sciences

Robert L. Sani, U. Colorado
Discipline: Chemical engineering

M. Sanford Sillman, U. Michigan
Discipline: Atmospheric chemistry

Julia M. Slingo, U. Redding, U.K.
Discipline: Physical processes in GCMs

Gregory Taylor, Calif. State U., Chico
Discipline: Atmospheric sciences

Morton G. Wurtele, U. Calif., Los Angeles
Discipline: Atmospheric dynamics

Robert B. Wilhelmson, U. Illinois, Urbana/Champaign
Discipline: Meteorology and computer science

Former Staff

Over the past two years, a number of scientific and administrative staff have concluded their service with the Atmospheric and Geophysical Sciences (AGS) Program, generally either retiring or moving on to other projects within and outside of the Laboratory. We express our appreciation to them for their contributions to the AGS Program and wish them well in their new endeavors. These individuals include Rich Belles, Marilyn B. Borton, Sharon Braley, George Greenly, Doris Gresho, Glenn Hage, Pearline Hassan, Linda Kennedy, Richard J. Mayfield, Michel McCoy, Broox L. McLemore, Mary Meyer, Richard Procassini, Lonette Robinson, Leonard Rosen, Debbie Sparkman, Sandy Taylor, Conrad Wilgus, Carolyn Wimple, David Wright, and Howard Zangari.

Special Outside Staff Activities

Michael M. Bradley
Chairman, Cloud Physics Committee of the Interagency Lightning Threat Warning Working Group

Marvin H. Dickerson
Member, DOE Subcommittee on Dose Assessment; Member, DOE ARM Management Team; Team Leader, DOE ARM Experiment Support

Jane E. Dignon
Member, International Global Atmospheric Chemistry Project, Committee on Global Emissions Inventories

Donald L. Ermak
Chairman, Joint Army/Navy/NASA/Air Force Safety and Environmental Protection Subcommittee Panel on Atmospheric Hazards and Modeling

Connee S. Foster
Member, Emergency Preparedness Special Interest Group of Training Resources and Data Exchange

W. Lawrence Gates
Editor, *Climate Dynamics;* Lead author, Intergovernmental Panel on Climate Change assessment report; Member, Working Group on Numerical Experimentation, World Climate Research Programme; Member, Advisory Panel of the Scientific Computing Division, National Center for Atmospheric Research, Boulder, Colorado; Member, International Commission on Climate, International Association of Meteorology and Atmospheric Physics; Member, National Scientific Advisory Committee, Desert Research Institute, University of Nevada, Reno; Member, Scientific Advisory Committee, Climate System Modeling Program, University Corporation for Atmospheric Research; Chairman, Steering Group on Global Climate Modelling, World Climate Research Programme; Member, ad hoc Study Committee for the Climate Variability program, World Climate Research Programme

Philip M. Gresho
Co-chief Editor, *International Journal for Numerical Methods in Fluids*; Adjunct Professor, Chemical Engineering, University of California, Davis

Paul H. Gudiksen
Member, Environmental Transport Working Group 7.1, U.S.–U.S.S.R. Joint Coordinating Committee for Civilian Nuclear Reactor Safety; Member, Planning and Advisory Panel for the Atmospheric Studies in Complex Terrain program; Member, Program Committee for Commission of European Communities/DOE Workshop on Real-time Emergency Response

John M. Leone, Jr.
Member, American Meteorological Society Committee on the Meteorological Aspects of Air Pollution

Michael C. MacCracken
Associate Editor, *Journal of Climate*; Chairman, Evaluation Review Panel of the U.S.–Canada Acid Precipitation Modeling Task Force; Member, Science Team, Climate System Modeling Project, University Corporation for Atmospheric Research; Member, Effects Subpanel, National Academy of Sciences Study on the Policy Implications of Greenhouse Warming; Member, Technical Advisory Panel on the Global Change Research Program, Environmental Protection Agency; Member, International Commission on Climate, International Association of Meteorology and Atmospheric Physics; Member-at-large, Committee for Section W, Atmospheric and Hydrologic Sciences, American Association for the Advancement of Science (1991–95); Member, Research Advisory Board, University of Nevada, Las Vegas

Joyce E. Penner
Associate Editor, *Journal of Geophysical Research*; Member, Modeling Advisory Committee, California Air Resources Board; Member, Atmospheric Chemistry Committee, National Academy of Sciences; Member, Board of Directors, American Association for Aerosol Research; Member, Committee on Atmospheric Chemistry, American Meteorological Society; Chairman, DOE ARM Aerosol Working Group; Member, NASA Global Tropospheric Chemistry Advisory Committee

Gerald L. Potter
Member, Executive Committee of DOE Energy Research Supercomputer Users Group (Chairman, Mass Storage Subcommittee); Member, Institute of Electrical and Electronics Engineers, Mass Storage Symposium Organizing Committee; Member, Executive Committee of National Storage Laboratory

Thomas J. Sullivan
Member, DOE Federal Radiological Monitoring and Assessment Center, Evaluation and Assessment Working Group; Member, DOE Subcommittee on Dose Assessments; Member, LLNL Tritium Environmental Impact Assessment Working Group

Donald J. Wuebbles
Lead author, Intergovernmental Panel on Climate Change assessment report; Member, Advisory Panel for National Institute for Global Environmental Change, Southern Region; Member, International Association for Geomagnetism and Aeronomy, Working Groups on Solar Radiation and on External Forcing of the Middle Atmosphere; Member, International Commission on Modeling of the Upper Atmosphere, Working Group on Modeling of the Middle Atmosphere; Member, NASA Advisory Panel on the High Speed Research Program; Member, International Geosphere–Biosphere Programme, Working Group on Stratospheric Influences on Tropospheric Climate; Member, National Research Council, Working Group on Solar Influences

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[1]Computation Organization, LLNL
[2]A-Division, Defense Sciences Department, LLNL
[3]Electronics Engineering Department, LLNL
[4]EG&G, Pleasanton, California
[5]National Energy Research Supercomputer Center, LLNL
[6]Education Program, LLNL
[7]L-Division, Nuclear Test-Experimental Science, LLNL
[8]Postdoctoral Awardee University of California Institutional Collaborative Research program
[9]Computational Physics Division, Physics Department, LLNL
[10]Kaiser Engineers, Livermore, California
[11]Environmental Sciences Division, Physics Department, LLNL
[12]Mechanical Engineering Department, LLNL
[13]Postdoctoral Awardee, Oak Ridge Institute for Science and Education
[14]University of California, Santa Cruz
[15]Université de Paris
[16]Kirk Meyer Services (KMI), Livermore, California

Appendix B. Interactions with Other Laboratories, Universities, and Institutes

Atmospheric Flow and Dispersion Modeling Group

Vladimir Gavrilov (Institute of Experimental Meteorology, Obninsk, Russia) is collaborating with us on the evaluation of three turbulent diffusion models: the Eulerian classical eddy-diffusivity model, and the Lagrangian random-displacement and random-velocity-increment (Langevin) models.

Jerry Havens and Tom Spicer (University of Arkansas) are using our three-dimensional heavy-gas model (FEM3A/FEM3B) to study the dispersion of liquefied natural gas and potential mitigating techniques.

Ray Joblonski (U.S. Army Chemical Research Development and Engineering Center) is using our three-dimensional heavy-gas model (FEM3A/FEM3B) in studies related to the atmospheric dispersion of chemical agents.

Allan Ross (University of California, Davis) is helping us evaluate a more advanced turbulence model for simulating flow around buildings. He is also helping us to implement this model into our building-wakes model.

Brian Sawford (Commonwealth Scientific and Industrial Research Organization, Division of Atmospheric Research, Mordialloc, Victoria, Australia) has been providing information to us on the Langevin model for turbulent diffusion.

Su-Tzai Soong (University of California, Davis) is collaborating with us on a joint project to study the effects of global change on the climate of California.

Eugene Takle (Iowa State University) is using our SABLE model to study Florida sea breeze events.

Model Applications and Nuclear Effects Group

Natalia Klepikova and Vladimir Gavrilov (Institute of Experimental Meteorology, Obninsk, Russia) are working with us on the development of improved turbulence parameterizations for atmospheric dispersion models and on the development and application of long-range dispersion models.

Sergei Pitovranov (Institute of Systems Analysis, Moscow) is helping us with the development of a methodology for integrating radiological measurements with model predictions for source-term reconstruction.

Program for Climate Model Diagnosis and Intercomparison

Robert Cess (State University of New York, Stony Brook) is working with us on studies of cloud-radiation and other climate feedbacks.

Ulrich Cubasch and Benjamin Santer (Max Planck Institute for Meteorology, Hamburg, Federal Republic of Germany) are working with us on analyses of coupled ocean-atmosphere GCM simulations and interannual variability.

Sultan Hameed (Institute for Terrestrial and Planetary Atmospheres, State University of New York, Stony Brook) is working with us on analyses of coupled ocean-atmosphere GCM simulations and interannual variability.

Jean-Jacques Morcrette (European Centre for Medium Range Weather Forecasts, Reading, United Kingdom) is working with us on analysis of model simulations of high-frequency tropical variability.

Timothy Palmer (European Centre for Medium Range Weather Forecasts, Reading, United Kingdom) is working with us on analysis of model simulations of Indian monsoon variations.

Julia Slingo (University of Reading, United Kingdom) is working with us on analysis of high-frequency tropical variability.

Atmospheric Model Intercomparison Project participants include about 30 modeling groups from around the world. For a complete listing of participants, refer to Table 1 of the article "Understanding Why Climate Models Agree and Disagree" in Section 2.

Cloud Modeling and Experiment Support Group

Donna Edwards (Sandia National Laboratories, Livermore) works with us as a member of the DOE ARM Data Management Team. She is responsible for configuration management of software implemented at the ARM Experiment Center.

Jim Liljegren (Battelle Pacific Northwest Laboratory) works with us as a member of the DOE ARM Experiment Support Team. He is liaison between ARM and Science Team members for the IRF GMS. He is also instrument mentor for the microwave radiometer.

Nancy Miller (Battelle Pacific Northwest Laboratory) works with us as a member of the DOE ARM Experiment Support Team. She is responsible for developing data quality control experiments.

Ron Melton (Battelle Pacific Northwest Laboratory) is a leader of the DOE ARM Data Management Team and is responsible for implementation of the ARM Experiment Center.

Joyce Tichler (Brookhaven National Laboratory) is a member of the DOE ARM Data Management Team. She works with us to identify and link external sources of data to ARM.

Atmospheric Microphysics and Chemistry Group

Carmen Benkovitz (Brookhaven National Laboratory) is coordinating research in NO_x and SO_2 emissions under the International Global Atmospheric Chemistry Program.

Daniel Botkin (University of California, Santa Barbara) advises us about the formulation of models that will simulate vegetation growth and biogeochemical uptake and emissions.

Robert Dickinson (Arizona State University) is working with us to evaluate the climatic effects of aerosols from biomass burning.

Steven Ghan (Battelle Pacific Northwest Laboratory) is collaborating with us on a jointly funded proposal under the DOE ARM program to improve the treatment of cloud optical properties in climate models.

Benjamin Graboske (University of California, Berkeley) is using our global tropospheric chemistry model to study the cycle of ^{7}Be in the atmosphere.

Hans Graf (Max Planck Institute for Meteorology, Hamburg, Federal Republic of Germany) is jointly designing with us a simulation of the effects of sulfur aerosols on clouds using our tracer transport model and the ECHAM climate model [the Max Planck Institute (Hamburg) version of the ECMWF model].

Sonia Kreidenweis (Colorado State University) is working with us to develop our treatment of H_2SO_4 vapor condensation and nucleation in our global tropospheric chemistry model.

Cindy Nevison (Stanford University) is using our global tropospheric chemistry model to study the cycle of N_2O in the atmosphere and to develop an estimate of N_2O emissions.

Tihamir Novakov (Lawrence Berkeley Laboratory) is working with us to estimate the black carbon emissions in the atmosphere and the effects of aerosols on cloud droplet concentrations.

Joe Pinto (Environmental Protection Agency, Research Triangle Park, North Carolina) is developing an updated chemical mechanism for oxidation of methane and propane that will be incorporated into our global tropospheric chemistry model.

Sanford Sillman (University of Michigan) is working with us to develop a fast, efficient numerical scheme to treat ozone photochemistry.

Global Radiation, Chemical, and Dynamical Interactions Group

Nancy Brown (Lawrence Berkeley Laboratory) developed jointly with us a new proposal to NASA on uncertainty analyses.

Julius Chang (State University of New York, Albany) is collaborating with us on the NASA Upper Atmosphere Research Satellite project and studies of interactions between the stratosphere and troposphere.

Ray Cline (Sandia National Laboratories, Livermore) collaborated with us on a DOE CHAMMP project to parallelize our two-dimensional global chemistry model.

John DeLuisi (National Oceanic and Atmospheric Administration) is collaborating with us on studies relating to ozone measurements and analysis of trends in ozone.

Jae Edmonds (Battelle Pacific Northwest Laboratory) is working with us on studies relating to greenhouse gases, climate change, and their relationship to economic factors.

Stan Greenfield and Paul Guthrie (Systems Applications Incorporated, San Raefel, California) are coordinating research with us for the Environmental Protection Agency to determine how best to represent local and regional photochemistry effects in two- and three-dimensional global models.

Gordon Hamilton, Moe Metwally, and Alan Mortlock (McDonnell Douglas Corporation) are working with us on studies for NASA relating to aircraft emissions.

Hal Johnston (University of California, Berkeley) is collaborating with us on studies of heterogeneous chemistry mechanisms in the stratosphere and the effects of aircraft on stratospheric ozone.

Judith Lean (Naval Research Laboratory) is working on studies of solar variations and their effects on the stratosphere in coordination with our modeling activities.

Andrew Matthews and Richard McKenzie (Department of Scientific and Industrial Research, Lauder, New Zealand) are working with us on studies relating to the NASA Upper Atmosphere Research Satellite measurements of ozone, nitrogen dioxide, and solar flux.

Jim Miller (NOAA National Meteorological Center) **and Greg Reinsel** (University of Wisconsin) are collaborating with us on studies to establish scientific relationships in observed ozone and temperature trends.

Dirk Offermann (University of Wuppertal, Federal Republic of Germany) is working with us on studies of diurnal variations in nitrogen dioxide.

John Pyle (Cambridge University) **and Susan Solomon** (NOAA Aeronomy Laboratory) and our group are re-examining the estimated ozone depletion potentials for chlorofluorocarbons, Halons, and their replacements.

Hersh Rabitz (Princeton University) developed jointly with us a new proposal to NASA on uncertainty analyses.

Richard Rood (NASA Goddard Space Flight Center) is coordinating NASA's three-dimensional model development activities and advanced numerical transport scheme studies with our model development activities.

Keith Ryan (Commonwealth Scientific and Industrial Research Organization, Sydney, Australia) is cooperating with us on the development of global atmospheric chemistry models.

Chris Webster (Jet Propulsion Laboratory) is working with us on a correlative measurement project as part of the NASA Upper Atmosphere Research Satellite program.

Climate and Climate Change Group

Akio Arakawa, Carlos Mechoso, and Joseph Spahr (University of California, Los Angeles) have provided the UCLA AGCM for our use and are working with us to adapt it for use on massively parallel computers.

Tim Barnett (Scripps Institution of Oceanography) has advised us on using ocean models for tracer transport studies.

Wallace Broecker and colleagues (Lamont Doherty Geological Observatory) are developing a data set of ocean trace-species concentrations for use in verifying OGCMs.

Martin Hoffert (New York University) is collaborating with us on estimating limits of climate sensitivity as based on paleoclimatic data.

Christopher Kerr (NOAA Geophysical Fluid Dynamics Laboratory) has provided the GFDL Modular Ocean Model for our use and is working with us to adopt it for use on massively parallel computers.

Josef Oberhuber (Max Planck Institute for Meteorology, Hamburg, Federal Republic of Germany) has provided his isopycnal coordinate OGCM for studies of ocean tracer transport.

Sung-Hing Peng (Oak Ridge National Laboratory) is collaborating with us in a study of ocean uptake of radiocarbon and other species.

Alan Robock (University of Maryland) is collaborating with us in a study of the climatic effects of volcanic aerosols and sea-surface temperature anomalies.

Richard Somerville and Peter Norris (Scripps Institution of Oceanography) have contributed to our study of snow-albedo feedback.

Appendix C. Fiscal Year 1992 Funding by Sponsor*

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
DOE				
ARAC Operations	DP	3290	T. Sullivan	Develop and operate the ARAC service for DOE, DOD, and other agencies
Technology Development	DP	300	P. Gudiksen	Improve long-range diagnostic atmospheric-dispersion models
Support for Complex Terrain Studies	ER	313	P. Gudiksen	Help plan and participate in ASCOT field studies designed to evaluate performance of mesoscale models in complex terrain
Mesoscale Emergency Response	ER	300	J. Leone	Develop and test complex-terrain atmospheric boundary-layer models and apply to emergency response situations
Atmospheric Chemistry Program/NARE	ER	100	J. Penner	Modeling in support of DOE's participation in the NARE
Cloud-Drop Effects of Aerosol Concentrations	ER	56	J. Penner	Effects of aerosols on cloud-drop concentration
Climate Linkages: The Role of Aerosols	ER	318	J. Penner	Effects of aerosols on climate
Trace Gases in the Global Atmosphere	ER	318	D. Wuebbles	Evaluate the interactions of atmospheric chemistry and climate
PCMDI	ER	3762	W. L. Gates G. Potter	Conduct model intercomparison and diagnostic studies; reanalyze observational data sets
CHAMMP: Program Support	ER	235	M. MacCracken	Support for CHAMMP Science Team leader
CHAMMP: Climate Systems Modeling	ER	450	W. Dannevik A. Mirin	Conversion of atmospheric and oceanic GCMs to massively parallel computers

*Acronyms and abbreviations are defined in Appendix G.

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
CHAMMP: Atmospheric Chemistry and Climate Predictability Toward an Advanced Climate Model	ER	300	D. Wuebbles J. Penner	Develop an advanced three-dimensional chemical-transport model of the global atmosphere
Climate Management Support	ER	425	M. MacCracken	Assist DOE's Carbon Dioxide Research Program with scientific reviews and interactions. Support the LDGO contract to develop ocean tracer data sets
Climate Modeling	ER	360	K. Taylor	Conduct modeling studies investigating model sensitivity and rate of climate change
Global Climate Change Curriculum Development	ER	450	M. Perry	Develop and disseminate K–12 greenhouse-gas curriculum materials
U.S./Russian Bilateral Agreement: Atmospheric Dispersion Modeling	EH	190	P. Gudiksen	Scientific collaboration on the development and evaluation of atmospheric dispersion models
ARAC Support of Hanford Site	EM	100	T. Sullivan	Analyze emergency-response planning requirements for possible atmospheric release and dispersal of radionuclides from the Hanford waste-storage tanks
ARAC NR Sites	NE	272	T. Sullivan	Provide ARAC service to DOE NR sites
Global Atmospheric Research Related to Energy/Climate Policy	PE	295	D. Wuebbles	Develop greenhouse warming potentials for use in prioritizing policy actions by greenhouse gas

Work for Others—DOE

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
Interfacing Between a Hierarchy of Numerical Models in ARM	LANL	180	J. Leone	Develop GCM cloud/radiation parameterization through the use of fine-scale atmospheric boundary-layer models
Tower Maintenance	EG&G/ Mound	7	T. Sullivan	Maintenance for ARAC tower

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
ARM Infrastructure Support and Directed Research	PNL	1000	M. Dickerson J. Penner M. Bradley	Participate as part of the ARM management team and coordinate the experiment support activities
Modeling in Support of DOE's Participation in the Kuwait Oil Fire Experiment	PNL	25	J. Penner	Develop meteorological fields for use by GRANTOUR and G-CHEM covering the time period of the PNL flights near Kuwait. Run GRANTOUR for the time of experiments
Parameterization of Cloud-Drop Number Concentration in CCM1	PNL	30	J. Penner	Develop parameterization for treating the relationship between cloud-drop size distribution and aerosol concentration
Detection of Climate Change Planning Group	PNL	28	M. MacCracken	Participate in a DOE-sponsored project to plan a research and monitoring program focusing on detecting climatic change and determining the component due to increasing concentrations of greenhouse gases
Tower Maintenance	SNLL	3	T. Sullivan	Maintenance for ARAC Tower
Global Greenhouse Impact on Forcing of the California Climate	UCD/ NIGEC	47	R. Lee	Perform regional climate studies using output from GCMs to drive a regional model of California
LLNL				
ARAC ARG Support	LLNL	220	T. Sullivan	Support of DOE's ARG
Fallout Research	LLNL	550	T. Harvey	Maintain state-of-the-art fallout-prediction capabilities at LLNL
Incorporating Toxic Gas Capability in ARAC	LLNL	75	D. Ermak	Test dense- and toxic-gas dispersion simulation techniques suitable for inclusion in the ARAC emergency-response system
Ozone Chemistry	LLNL	75	J. Penner	Develop a three-dimensional tropospheric ozone model
Climate and Aerosol Microphysics	LLNL	134	J. Penner	Develop a prognostic climate model parameterization to represent aerosol effect on clouds

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
Building Wake	LLNL	160	R. Lee	Develop the capability to simulate flows that contain pollutants around buildings using advanced FEM numerical models
Earth System Modeling	LLNL	1545	M. MacCracken J. Penner W. Dannevik C. Covey J. Kercher J. Houpis	Develop a coupled model of the atmosphere, ocean, and land-surface systems, including representation of global chemistry

Other Federal

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
ARAC	DOD	809	T. Sullivan	Develop and operate the ARAC service for DOD, DOE, and other agencies
Continuation of FEM3A Transfer to CRDEC	DOD/ USA	116	S. Chan	Consulting and training of CRDEC personnel on use of FEM3A dispersion model at Aberdeen Proving Grounds
TMD Lethality	DOD/ USA	115	T. Sullivan J. Ellis	Modify the ARAC meteorological models and transport/dispersion models to treat the evaporation and droplet coalescence of chemical-warfare liquids dispersed as a result of a TMD intercept over a range of altitudes and meteorological conditions
Dense Gas Dispersion	DOD/ USAF	85	D. Ermak	Develop an emergency-response dispersion model capable of treating the behavior of heavier-than-air gases in complex terrain
Model Integration	DOD/ USAF	463	P. Gudiksen D. Rodriguez	Evaluate long-range models and integrate models with databases and computational system for USAF applications
ARAC NSY and Fleet HQ	DOD/ USN	607	T. Sullivan	Provide ARAC service, training, and exercises to selected NSY and Fleet HQ
SLAB	EPA	9	D. Ermak	Develop guidelines and operational procedures for using the LLNL-developed SLAB model to simulate the atmospheric dispersion of realistic, denser-than-air, toxic-gas releases

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
Global Change Influences	EPA	251	J. Penner D. Wuebbles	Assess state of knowledge, identify key sensitivities, and perform research needed to reduce uncertainties and provide needed knowledge on trends in atmospheric species and potential impacts on tropospheric chemistry and climate, especially tropospheric ozone
Two-Dimensional Modeling of Aircraft Global Impacts	NASA	140	D. Wuebbles	Study the environmental effects of current and potential future aircraft emissions
Sulfur Chemistry	NASA	144	J. Penner	Develop a global sulfur model including aerosol formation and cloud interactions
Zonally Averaged Chemical Transport Model of the Troposphere and Stratosphere	NASA	240	D. Wuebbles	Develop and apply a state-of-the-art, time-dependent, two-dimensional model for studying the coupling of chemical, radiative, and dynamical processes in the atmosphere; maintain and further develop the one-dimensional model
UARS	NASA	516	D. Wuebbles	Provide support to the UARS project during advanced definition phase and finalize details of theoretical investigation requirements

Non-Federal

ARAC Shipyard	General Dynamics	60	T. Sullivan	Provide ARAC service, training, and exercises
Atmospheric Methane	GRI	66	D. Wuebbles	Studies of the potential chemical and climatic effects related to emissions of methane
HSCT Study	McDonnell-Douglas	50	D. Wuebbles	Sensitivity studies of a matrix of possible future aircraft emissions
U.K. ARAC Support	U.K./MOD	13	C. Foster	Develop customized ARAC software, establish an ARAC link with the U.K., and participate in an annual exercise with the U.K.

Project Title	Sponsor	Projected Budget (K$)	Principal Investigator	Objective
DOE Capital Equipment				
ARAC equipment funds	DP	1400	T. Sullivan	Acquisition of ARAC center equipment
OHER equipment funds	ER	575	All ER Principal Investigators	Acquisition of OHER projects' equipment

Appendix D. Summary of Modeling Capabilities

We have developed a wide variety of modeling capabilities in the course of our many research efforts. This section is divided into six modeling categories. Each model is listed and briefly described under the category that best describes its primary application. The scientists currently having primary responsibility for each code are also listed; these individuals are not necessarily the developers of the model.

Species Transport and Diffusion Models

MATHEW/ADPIC Model

This three-dimensional Langrangian particle model calculates the transport and diffusion of pollutant puffs or plumes in a time-varying atmospheric boundary layer. ADPIC is based on simulation of particle transport using a three-dimensional, mass-conservative, time-varying wind field provided by the MATHEW code. We are using this computer model to simulate particulate and gaseous concentrations, the deposition of particles with given size distributions, and rainout (from one or more sources) to distances of several hundred kilometers. ADPIC calculations have been compared with measurements for (1) many field-diffusion experiments, including the Atmospheric Studies in Complex Terrain (ASCOT) program, and (2) emergency and assessment response, such as the 1979 Three Mile Island incident, the subsequent Presidential Commission investigation, and the 1986 Chernobyl reactor accident. MATHEW/ADPIC is the chief model of the Atmospheric Release Advisory Capability (ARAC). A new version of the ADPIC model allows for statistical methods to deal with complex dispersion scenarios.
Contact: Rolf Lange

HMEDIC/HADPIC

HADPIC is a version of the ADPIC model modified to provide a capability to model transport and diffusion of pollutant clouds in the troposphere of the Northern Hemisphere using three-dimensional wind fields. These wind fields are constructed in the ARAC central facility from U.S. Air Force Global Weather Central (AFGWC) gridded wind data. HMEDIC is a data-handling and interpolation code that processes the AFGWC gridded data, either analysis or forecast, into three-dimensional arrays. HADPIC provides as output the pollutant concentrations at selected regions over the Northern Hemisphere. The code was used to simulate the time and space evolution of the 1986 Chernobyl reactor accident.
Contacts: Rolf Lange, Thomas J. Sullivan, Robert P. Freis, Daniel J. Rodriguez

GRANTOUR Tracer-Transport Model

GRANTOUR is a global atmospheric model that uses prescribed winds to transport species using a Lagrangian-sampler-parcel approach to calculate advection of tracers very accurately. The model can also calculate, if appropriate, scavenging (given precipitation rates), coagulation, dry deposition, mixing between air parcels, and radioactive decay. The model has been used to study the movement and dispersion of smoke and radionuclides in an unperturbed atmosphere using winds from the National Center for Atmospheric Research (NCAR) or Oregon State University (OSU) general circulation models (GCMs). The model has also been modified to represent atmospheric chemistry (see GRANTOUR Chemistry and Aerosol Model).
Contacts: John J. Walton, Joyce E. Penner

Advection-Diffusion FEM Model

This two-dimensional code solves the advection-diffusion equation (for concentration, for example) in arbitrary geometry and in which a fixed velocity field is specified as input data. Either time-dependent or steady-state solutions are available. As a special case, the transient or steady diffusion equation can also be solved.
Contacts: Philip M. Gresho, Robert L. Lee

Tracer-Trajectory Model

This model uses data on winds and temperature to calculate trajectories on an irregular, continental-scale grid. A specified number of parcels, injected at different times, locations, and heights, can be used to represent an emission of an inert species and can be followed over periods of several days to several weeks. Parcel trajectories may be followed for (1) constant

height above terrain, (2) constant parcel potential temperature, or (3) constant parcel pressure. Dispersal of the tracer by eddy mixing (or diffusion) is not considered.
Contact: Ronald L. Baskett

ARAC INPUFF Model

This integrated puff model is a version of the Environmental Protection Agency's (EPA) INPUFF model. Some of the original capabilities have been eliminated to allow a simplified implementation for ARAC's Site Workstation system, and the output capabilities have been expanded to allow flexible contouring. ARAC's current implementation allows time-dependent meteorological and source-term specification while generating results on a square nested grid. Output can consist of either instantaneous or integrated air concentrations.
Contact: Kevin T. Foster

KDFOC2 Model

This versatile fallout model was developed to assess complex civil defense and military effects issues. Large technical and scenario uncertainties require a fast, adaptable, time-dependent model to obtain fallout results in complex demographic scenarios. The KDFOC2 capability and other databases available in G-Division provide the essential tools for considering trade-offs between various plans and features of different nuclear scenarios and for estimating the uncertainties inherent in the predictions.
Contacts: Ted F. Harvey, Leslie L. Edwards

GLODEP2 Model

The GLODEP2 model provides worldwide estimates of the surface deposition of radioactivity and the gamma-ray dose-to-man from intermediate and long-term fallout produced by nuclear explosions. The model is based on empirical relationships derived primarily from injection-deposition experience gained from the nuclear tests conducted by the U.S. and U.S.S.R. in 1958. If a nuclear power facility is destroyed (vaporized) and its debris behaves in the same manner as the radioactive cloud produced by the nuclear weapon that attacked the facility, the model can predict the gamma dose from this source of radioactivity. The model includes empirically derived gamma-dose relationships that account for meteorology, weathering, and terrain-roughness shielding at specific locations. As a comparison study, the gamma dose due to the atmospheric nuclear tests conducted during the period of 1951–1962 has been computed, and results compare well with observations.
Contacts: Leslie L. Edwards, Ted F. Harvey

PCAS1 Model

PCAS1 is a model for doing probabilistic consequence assessments. It is designed to calculate consequences from nuclear device accidents, including those undergoing assembly or transportation. In PCAS1, we have established some important "probabilistic protocols" that provide model and database interfaces linking sundry probabilistic parameters and models. PCAS1's principal predictions are the radiological insults to individuals (shown as frequency distributions of people vs dose), the areal deposition of fission products or plutonium, and the cumulative probability distribution of potential latent cancer fatalities. PCAS1 has the capability of mapping the U.S. population onto the deposition grid and of incorporating statistics of wind roses. PCAS1's suite of scenarios includes high-explosive explosions, fuel fires, propellant fires, and nuclear explosions. Uncertainties on respirable and aerosolized fractions have been included in past PCAS1 assessments.
Contact: Ted F. Harvey

Atmospheric Chemistry and Microphysics Models

One-Dimensional Chemical-Radiative-Transport Model

The one-dimensional chemical-radiative-transport model calculates globally averaged vertical profiles of relevant trace-gas concentrations in the troposphere and stratosphere. This model is a useful diagnostic and prognostic tool for studying chemical, radiative, and dynamical processes and interactions in the atmosphere. It has been used extensively for national and international investigations of the effects of potential chemical-emission scenarios upon the ozone layer and for studies related to climate change. Modes of model execution include diurnally cycled or diurnally averaged, for time-dependent scenarios, or rapidly obtained steady-state solutions. The model atmosphere extends from the ground to just above the stratopause (about 56 km) and is divided into 44 layers. The model chemistry currently includes about 150 chemical reactions among 50 species. The radiative treatment for photolysis reactions includes the effects of multiple scattering. Changes in radiatively active trace-gas concentration can be used to obtain new stratospheric radiative-equilibrium temperatures. Transport processes in the one-dimensional model are simulated by prescribed diffusion coefficients.
Contacts: Donald J. Wuebbles, Peter S. Connell, Keith E. Grant, Douglas E. Kinnison

Two-Dimensional Atmospheric Research Program—T(D)ARP

The LLNL zonally averaged two-dimensional chemical-radiative-transport model is used in a wide range of studies related to concerns about global ozone and the effects of chemical processes on climate. These include studies to determine the effects on tropospheric and stratospheric ozone resulting from emissions of chlorofluorocarbons (the chlorine-containing CFCs), Halons (brominated halocarbons), methane (CH_4), and other surface-emitted trace gases, from current and potential aircraft emissions, from atmospheric nuclear explosions, from volcanic eruptions, and from natural variations in the solar flux. The model currently determines the atmospheric distributions of 54 chemically active atmospheric trace constituents in the troposphere and stratosphere. The photochemistry in the LLNL two-dimensional model represents the tropospheric and stratospheric reactions of all of the relevant species containing oxygen, nitrogen, hydrogen, chlorine, and bromine. The model includes photodissociation reactions resulting from the interaction of these species with the actinic solar flux. The photolytic loss rate constants are calculated by integrating the product of absorption coefficient, quantum yield, and solar flux over wavelength (175–735 nm). The exoatmospheric solar flux is based on satellite measurements. The solar flux is then calculated as a function of altitude, latitude, and season, including the effects of absorption by molecular oxygen and ozone and multiple molecular (Rayleigh) scattering. The absorption cross sections and quantum yields include temperature and pressure dependence where appropriate and available.

The model can be used to determine either the full diurnal variation or the diurnally averaged concentration of each calculated constituent. Because of its computational efficiency, the diurnal-averaged version of the model is used in most studies. The nonlinearity of the photochemistry with respect to diurnal averaging is accounted for through the calculation of individual altitude, latitude, and seasonally varying factors for each photochemical process. In the model, the trace constituents are transported by both the zonal mean motions (winds) of the atmosphere and the local deviation from the mean flow (termed eddy transport). The circulation field in the LLNL two-dimensional model is currently obtained diagnostically on the basis of a climatological temperature distribution. The zonal mean winds in the meridional and vertical directions are obtained using the net atmospheric heating rates. The net heating rates are calculated on the basis of knowledge of the temperature and chemical-species distribution, and they include latent heating. Eddy-transport effects are estimated in the form of diffusion terms. The transport of chemical species is accomplished through both advection and turbulent eddy transport.

Contacts: Donald J. Wuebbles, Peter S. Connell, Keith E. Grant, Douglas E. Kinnison, Douglas A. Rotman

GRANTOUR Chemistry and Aerosol Model

The GRANTOUR model calculates the three-dimensional distribution of gas-phase and aerosol-phase species using a Lagrangian formulation. Current applications use simplified chemical interactions to describe the global distributions of reactive nitrogen and sulfur species. The reaction set is being extended to treat more complete chemical interactions. The model is also capable of describing simple aerosol interactions including the effects of aerosol coagulation, the formation of aerosol particles from the gas-phase oxidation of sulfur compounds, and the effects of aerosol population on cloud-droplet-number distributions. In most applications, the wind and precipitation fields from the NCAR Community Climate Model (CCM) are used to drive the species transport and removal, although the model has been linked to other climate models as well. The model can also be run interactively with the NCAR CCM to study the effects of aerosols on climate and climate change.

Contacts: Joyce E. Penner, John J. Walton, Cynthia S. Atherton

Atmospheric-Kinetics Model

This model is used for detailed studies of the chemical and photochemical kinetics (no transport) of the troposphere and stratosphere. It uses advanced mathematical methods to study the kinetics of a well-mixed cell, including the effects of solar absorption for photodissociation processes. This model has been used to evaluate the sensitivity of reaction mechanisms to deficiencies in knowledge of reaction rates, quantum yield, reaction ensemble, solar constant, and reactant concentrations. The model has also been useful for studying the feasibility of employing reduced-reaction sets in more complex atmospheric models.

Contacts: Donald J. Wuebbles, Joyce E. Penner, Peter S. Connell

Atmospheric-Kinetics and Aerosol-Nucleation Model

This model is used for detailed studies of the chemical and photochemical interactions of species leading to the formation of condensable products in the atmosphere.

The condensable products may form new aerosol particles (nucleation) or may condense on pre-existing particles. The aerosol-number concentration and mass mean diameter are calculated for two separate aerosol modes. The model has been useful for studying the atmospheric conditions leading to new particle formation and the composition of aerosols in the atmosphere.
Contacts: Joyce E. Penner, Sonia Kreidenweis (Colorado State University)

CAMP Model

The CAMP computer code numerically solves the atmospheric microphysical equations in a well-mixed spherical or plume-like parcel of air, water vapor, liquid water, and aerosols. The aerosols may be of differing compositions of water-soluble and insoluble materials. The parcel may be pseudo-adiabatic, where the dynamics are driven by the buoyancy forces acting on a background sounding, or they may be based on a specified "trajectory" for which the dynamics are determined by a cloud-scale dynamics code. The parcel may entrain background aerosols and drops. Given an aerosol-number density distribution and/or a drop-number density distribution, the code solves for the time evolution of the distributions as well as for the parcel temperature and saturation. The microphysical processes included are condensation/evaporation of water vapor, nucleation of aerosols to form drops, aerosol coagulation, drop coalescence, interstitial aerosol collection by drops, and drop break-up—all on spherical particles. The model does not yet consider ice processes, which may be important in some applications.
Contact: Catherine Chuang

Aerosol-Coagulation Model

This model solves the kinetic coagulation equation, which determines the evolving size distribution of an assemblage of aerosol particles. The model accounts for the collision of aerosol particles due to Brownian motion, turbulent motion, laminar-shear flow, and sedimentation. Dispersion of the aerosol is accounted for by a dilution-time constant specified from observations or calculations. A submodel is available to calculate the absorption and scattering cross section of the aerosol. The model has been applied as a Lagrangian-parcel model to describe the evolution of the size distribution and optical characteristics of smoke and dust particles after a nuclear war.
Contact: Joyce E. Penner

Radiative-Transfer Models

SWPAK

This model computes upward and downward ultraviolet and visible radiation fluxes given atmospheric vertical profiles of pressure, temperature, and concentrations of O_2, O_3, and NO_2. The calculated fluxes can be used by chemical-radiative-transport models to calculate layer heating rates or, with additional driver routines, photodissociation rates. The formulation of this model accounts for multiple scattering and allows inclusion of clouds and aerosols as well as absorbing gases. The solar spectrum and pertinent absorption cross sections are divided into 148 wavelength bins between 133.75 and 730 nm. Advantage is taken of each wavelength bin constituting an independent radiation-transfer problem to allow the coding to vectorize over wavelength bins when compiled on the Cray-1 or Cray-XMP. For each layer, the scattering and absorption of diffuse incident radiation is treated using the Sagan and Pollack two-stream algorithm. Scattering and absorption from the direct solar beam are treated using the delta-Eddington approximation. The effects of the separate layers are combined using the adding technique.
Contact: Keith E. Grant

Wide-Band IR Model for Cooling Rates from CO_2, H_2O, and O_3

The initial version of this model was obtained from Harshvardhan et al. ["A Fast Radiation Parameterization for Atmospheric Circulation Models," *J. Geophys. Res.*, **92**(D1) 1009–1016 (1987)]. The model is based on the far-wing scaling approximation and k-distribution approaches described in a series of papers by M.-D. Chou and coworkers [M.-D. Chou, "Broadband Water Vapor Transmission Functions for Atmospheric IR Flux Computations," *J. Atmos. Sci.*, **41**(10) (1984); M.-D. Chou and A. Arking, "Computation of Infrared Cooling Rates in the Water Vapor Bands," *Am. Met. Soc.*, **855** (1980); M.-D. Chou and L. Kouvaris, "Monochromatic Calculations of Atmospheric Radiative Transfer due to Molecular Line Absorption," *J. Geophys. Res.*, **92**(D3) 4047–4055 (1986); and M.-D. Chou and L. Peng, "A Parameterization of the Absorption in the 15 μm CO_2 Spectral Region with Application to Climate Sensitivity Studies," *J. Atmos. Sci.*, **40**(9) (1983)]. The model was developed to meet requirements for use in GCMs. It is computationally efficient in its basic algorithm,

and it is written to vectorize over separate vertical columns. The original model has required modifications for sufficient accuracy to be obtained at stratospheric pressure less than 3 mbar.
Contact: Keith E. Grant

Narrow-Band IR Model

The initial version of this model was obtained from David Kratz (NASA/Goddard) with parameters for CO_2, H_2O, O_3, CH_4, and N_2O. Parameters for CFCs, including temperature dependence, await detailed spectroscopic measurements. Restructuring and vectorization at LLNL have decreased the running time on a Cray-XMP to about 4 s using 31 vertical levels and an 8-point Gaussian integration over angle of propagation. Further reductions in running time are likely via parallelization. The narrow-band model is an extremely useful tool for analysis of the radiative forcings from changes in the vertical profiles of trace gas concentrations. However, even with vectorization, computer-time requirements limit the usefulness of the narrow-band model as an interactive part of GCMs and chemical-radiative-transport models.
Contact: Keith E. Grant

MIEV Model

The Mie scattering code developed by Wiscombe ["Improved Mie Scattering Algorithms," *App. Opt.*, **19** 1505–1509 (1980)] is being used to calculate the extinction and scattering efficiencies and the asymmetry factors for atmospheric aerosol particles, assuming the aerosols are homogeneous spheres. These parameters are integrated over the aerosol size distribution to produce integrated extinction, absorption, and asymmetry factors for the aerosol as a function of wavelength.
Contact: Charles R. Molenkamp

LOWTRAN7

The LOWTRAN7 model was developed at the U.S. Air Force Geophysics Laboratory. It calculates atmospheric transmittance, atmospheric background radiance, direct solar irradiance, and singly and multiply scattered solar and thermal radiance. The spectral resolution of the model is 20 cm^{-1}. Representative atmospheric, aerosol, cloud, and rain models are provided in the code options to replace them with specified or measured values. We are currently using LOWTRAN in cloud-free conditions to calculate upward solar and infrared fluxes at the top of the atmosphere, and downward infrared and direct and scattered solar fluxes at the surface, for a variety of atmospheric aerosols.
Contact: Charles R. Molenkamp

Atmospheric-Dynamics and Mesoscale Models

SLAB Dense-Gas-Dispersion Model

This code simulates the atmospheric dispersion of denser-than-air releases. The types of releases treated by the model include a ground-level evaporating pool, an elevated horizontal jet, a stack or vertical jet, and an instantaneous volume source. Except for the evaporating pool source, which is assumed to be all vapor, each of the other sources may be a two-phase mixture of vapor and liquid droplets. Source duration may be any finite length of time. SLAB simulates atmospheric dispersion by solving spatially averaged forms of the conservation equations of mass, momentum, energy, and species, along with cloud-width and length equations and the equation of state, using the Runge-Kutta method. The code is one-dimensional, with downwind distance being the independent variable; however, the full three-dimensional concentration distribution is determined by using similarity profiles based on the calculated cloud height, length, and width. Within SLAB's mathematical framework of heavy-gas dispersion, there is a natural progression toward neutrally buoyant trace-gas dispersion, allowing for calculations down to the lowest-desired concentration levels. The main advantage of SLAB over more complex heavy-gas models is its low computing cost. Typical simulations require only ~1 min on a microcomputer.
Contact: Donald L. Ermak

FEM3/FEM3A/FEM3B Dense-Gas Dispersion Models

These codes were developed primarily to simulate the atmospheric dispersion of heavier-than-air gas and liquid releases. A modified Galerkin finite-element method was employed to solve the time-dependent conservation equations of mass, momentum, energy, and species of the dispersed material together with the ideal gas law for the density of the mixture. A generalized anelastic approximation was invoked to preclude sound waves and yet allow large-density variations in space and time. Turbulence is parameterized via a K-theory submodel, and heat transfer from the ground surface into the vapor cloud is also

accounted for. Each of the codes can solve two- and three-dimensional problems, including treatment of variable terrain and finite-duration or continuous releases. In FEM3, an option exists for solving the Boussinesq equations as well. In FEM3A and FEM3B, instantaneous sources and obstructions are also treated. In addition, a phase-change submodel is available for handling the phase transitions (between vapor and droplets) of the dispersed material. In FEM3B, the model has been further enhanced to accurately conserve species mass and total mass for problems involving large density variations.
Contacts: Stevens T. Chan, Philip M. Gresho

FEM-PBL

This model, derived from FEM3, was developed to simulate planetary boundary-layer flow over complex terrain. It calculates the spatial and temporal distribution of velocity, pressure, potential temperature, and mixing ratios of liquid water, water vapor, and an inert tracer in two or three dimensions. The nonhydrostatic, Boussinesq equations with constant rotation form the basic dynamical framework of the model. Boundary-layer turbulence is parameterized via one of three K-theory models: an O'Brien cubic parameterization, a local Richardson-number-dependent parameterization, or a specified constant *K*. The model contains a nonlinear phase-change model to describe the effects of evaporation and condensation of water. As in FEM3, multilinear velocity, piecewise constant pressure finite elements are used in space, while a modified, explicit forward-backward Euler scheme is used to advance the spatially discrete equations in time. This combination of methods allows detailed representation of complex terrain, easy implementation of variable grids, and efficient performance.
Contacts: John M. Leone, Jr., Robert L. Lee

SABLE

This model has been developed to model atmospheric boundary-layer flows over moderate terrain on horizontal scales of a few hundred to 1000 kilometers. In contrast to FEM-PBL, SABLE solves the hydrostatic, anelastic equation set with constant rotation. Boundary-layer turbulence is parameterized via one of three K-theory models: an O'Brien cubic parameterization, a local Richardson-number-dependent parameterization, or a specified constant *K*. A mixture of multilinear finite elements and centered finite differences are used in space, while a semi-implicit scheme is used to advance the spatially discrete equations in time. This combination allows detailed and efficient representation of the terrain, easy implementation of variable grids, and accurate and cost-effective performance for simulations that do not require the more expensive nonhydrostatic equations.
Contacts: John M. Leone, Jr., Stevens T. Chan

FEMTKE Building Wakes Simulation Model

This model was developed to simulate flow around structures, such as buildings or building complexes. The code is a spin-off from the FEM nonhydrostatic Planetary Boundary Layer Model (FEM-PBL) with the K-theory model replaced by a more sophisticated *k-e* (two-equation) turbulence model. The FEM and time-integration procedure follows that of the former model with the exception that the source terms in the *k* and *e* equations are computed semi-implicitly. Buildings are represented numerically in the model as a collection of "solid" elements within which all of the calculated variables are taken as zero. For dispersion simulations, the calculated velocity fields are saved on disk and used as input for driving ADPIC. Although computations with FEMTKE must be performed on the Crays, ADPIC calculations and postprocessing are done on local workstations.
Contact: Robert L. Lee

Cloud/Mountain Model

This model was originally designed for the numerical simulation of convective precipitating storms over complex terrain. It is also capable of simulating stratiform, precipitating orographic storms, hydrostatic and nonhydrostatic mountain waves, and the dynamics and microphysics of smoke plumes from intense fires. The model is two-dimensional, time-dependent, Eulerian, nonhydrostatic, and fully compressible. It is based on the three-dimensional cloud model of J. B. Klemp and R. B. Wilhelmson ["The Simulations of Three-Dimensional Convective Storm Dynamics," *J. Atmos. Sci.*, **35**, 1070–1095 (1978)]. Our implementation differs from their model in several major ways: It is formulated in terrain-following coordinates, it utilizes a Rayleigh sponge to simulate a radiative upper-boundary condition, it uses a different turbulence parameterization and different boundary conditions, it includes the complete pressure equation, and it uses no linearization to simplify the equations.
Contact: Michael M. Bradley

OCTET: Dynamical and Microphysical Plume, Storm, and Mesoscale Numerical-Simulation System

The OCTET Simulation System consists of eight numerical models that are applicable to many atmospheric phenomena and spatial scales, ranging from dry mesoscale circulations, to tornadoes, to the interaction of aerosols with liquid and frozen precipitation inside violent thunderstorms. The OCTET system uses the nonhydrostatic, compressible, three-dimensional dynamic framework of the Klemp-Wilhelmson storm model. The system has a modular structure so that new modeling capabilities can be added. The simplest model in the OCTET system has only 6 prognostic variables; the most complex model has more than 20 prognostic variables. The eight models in the OCTET system are capable of simulating both the dynamics and the microphysical processes in:

1. Dry mesoscale circulations.
2. "Warm" precipitating, convective, and stratiform clouds; and warm, moist, mesoscale circulations.
3. "Cold" ice-bearing (ice crystals, snow, graupel, and hail), convective, and stratiform clouds; and severe storm circulations including squall lines, gust fronts, microbursts, low-level wind shears, and tornadoes.
4. Lightning generation in severe electrified storms and storm complexes (projected capability, not operational in 1992).
5. Dry smoke plumes (e.g., from forest fires or from burning cities in postnuclear-exchange environments); and aerosol transport and diffusion in dry mesoscale circulations.
6. Smoke plumes in warm, moist atmospheres with condensation, liquid precipitation, and smoke scavenging and removal; and aerosol transport, diffusion, and hydrometeor-aerosol interactions in warm, moist, mesoscale circulations.
7. Smoke plumes in cold, moist atmospheres with condensation, freezing, liquid and solid precipitation, and smoke scavenging and removal; and aerosol transport, diffusion, and hydrometeor-aerosol interactions in cold, moist, mesoscale circulations.
8. Electrified smoke plumes; large, intense smoke plumes that interact with fire-forced, electrified, ice-bearing clouds; and aerosol transport, diffusion, and hydrometeor-aerosol and aerosol-aerosol interactions in mesoscale circulations in electrified atmospheres (projected capability, not operational in 1992).

Contact: Michael M. Bradley

CSU Mesoscale Model

We are using the Colorado State University (CSU) Mesoscale Model developed by R. Pielke and his students to simulate a variety of terrain and surface-forced mesoscale flows. This model is a hydrostatic, incompressible, primitive-equation model; it includes topography and a detailed boundary-layer parameterization. The flows are usually driven by surface heating, which is calculated by balancing the surface-energy budget at each grid point. Atmospheric heating by absorption and emission of long- and short-wave radiation is also included. The model is three-dimensional, but it can be run in a two-dimensional rectilinear mode. For our applications, the CSU Mesoscale Model has been enhanced by allowing clouds and fog to form in saturated regions and by greatly improving the long-wave radiation parameterization.

Contact: Charles R. Molenkamp

UCD/LLNL Regional Climate Model

This mesoscale climate model is being developed jointly by the University of California, Davis (UCD) and LLNL to assess the impact of CO_2-induced greenhouse warming on the regional climate. The model is equipped with explicit treatment of cloud microphysics and short- and long-wave radiation, and it is coupled to a multilayer soil model. The model can be nested within the National Meteorological Center operational analyses grid to investigate regional-scale flow where observational data are used as initial and later boundary conditions. This mesoscale model will also be nested within an appropriate GCM for climate-change studies. When completed, this model will be a tool for regional climate studies as well as for short-term local weather forecasting.

Contacts: Su-Tzai Soong (Land, Air, and Water Resources, UCD), Jinwon Kim, Robert L. Lee

OSU/LLNL Soil-Hydrology and Surface-Flux Model

This multilayer, soil-hydrology, surface-temperature, and mixing-ratio model was originally developed at Oregon State University (OSU) for use with the U.S. Air Force GCM. This model has been improved for better treatment of snow-covered surfaces, especially for very thin snow cover. Minor improvements have also been made to obtain a more exact solution for the surface energy balance equation and to include a nonuniform vertical distribution of the plant root zone. This model has been coupled with the UCD/LLNL regional climate model for climate studies. It can also run in a stand-alone mode using observed or model-generated meteorological conditions such as low-level wind, temperature, mixing ratio, and precipitation for soil and surface hydrology studies, and surface-flux estimation. Surface fluxes calculated from this model using observed meteorological conditions during the Hydrologic Atmospheric Pilot Experiment agree well with observed fluxes.

Contact: Jinwon Kim

Global Climate Models

LLNL/NCAR Community Climate Model

The National Center for Atmospheric Research (NCAR) Community Climate Model (CCM1) has been transferred to Livermore and adapted to the LLNL

computer systems. Its parameterization of solar radiation has been replaced with a two-stream, delta-Eddington model, which uses the cloud overlap scheme of Morcrette and Fouquart. Cloud optical depth is expressed in terms of cloud droplet-number concentration and cloud liquid-water content. The cloud liquid-water content is diagnosed from the simulated condensation rate. The cloud droplet number is either prescribed or predicted through coupling with the GRANTOUR aerosol-transport model. The direct radiative effects of aerosols can also be accounted for through coupling with GRANTOUR.
Contacts: Karl E. Taylor, Curtis C. Covey

LLNL/OSU General Circulation Model

The modified LLNL/OSU GCM is being used as a tool for understanding climate-model validation with satellite data and for developing a methodology for model intercomparison. The model has been used to explore causes of the differences among climate models, focusing specifically on differences in cloud forcing and cloud properties. A version of the model coupled to a two-level mixed-layer ocean model has been used in parallel integrations with both normal and doubled atmospheric CO_2. The results of these simulations are being used to determine the seasonal and geographical distributions of CO_2-induced climate changes, including the behavior of low-frequency phenomena such as the El Niño–Southern Oscillation. The model has also been coupled to the OSU 5-level ocean GCM.
Contact: Gerald L. Potter, W. Lawrence Gates

ECMWF Global Atmospheric Model

Through a cooperative agreement with the European Centre for Medium Range Weather Forecasts (ECMWF), the operational (cycle 33, 19-level) global atmospheric model is being used by G-Division's Program for Climate Model Diagnosis and Intercomparison (PCMDI). The model contains advanced radiation, cloud, and surface hydrology packages, and when run with assimilated, synoptic, initial data and observed sea-surface temperatures is probably the world's most accurate numerical weather-prediction model over the 1- to 10-day range. The model is initially being run over several years in four spectral resolutions (T21, T42, T63, and T106) to examine the effects of resolution on simulated climate and climate processes. An updated version (cycle 36) of the model is also available.
Contacts: W. Lawrence Gates, Gerald L. Potter

UCLA Atmospheric General Circulation Model

The UCLA atmospheric general circulation model (AGCM) is comprised of a hydrodynamics component based on the enstrophy-conserving finite-difference algorithm of Arakawa, with modified sigma vertical coordinates, as well as a suite of column-physics packages including boundary-layer parameterization, cumulus and large-scale precipitation processes, radiative transfer, and subgrid-scale turbulent diffusion. The hydrodynamics module in the original code version has been rewritten in contemporary programming style to include fully three-dimensional data structures, and the complete code has been adapted to massively parallel architectures using the domain-decomposition/message-passing approach. Column-physics packages in the new code version are designed in highly modular form, so that alternative modules can be easily substituted. This model is one of the baseline components in the LLNL Earth Systems Modeling package. A version has been adapted for the UNIX workstation environment, and a single-column version is under development to provide a convenient test-bed for column-physics package development and testing.
Contact: Michael F. Wehner, William P. Dannevik

Community Climate Model/GRANTOUR General Circulation Model

The GRANTOUR species-transport model and the NCAR/LLNL CCM1 have been interactively coupled so that the species concentrations in the GRANTOUR model may perturb the radiative calculation in the NCAR/LLNL CCM1 and so that the winds and precipitation in the NCAR/LLNL CCM1 control the transport and scavenging of species in GRANTOUR. This model is being used to study the potential climatic effects of tropospheric aerosols. Another version of GRANTOUR treats the global wet and dry deposition of nitric acid resulting from global sources of NO_x and a simple chemistry. This model can also be run in its uncoupled mode with NCAR/LLNL CCM1 meteorology.
Contact: John J. Walton

Two-Dimensional Climate Model

This zonally averaged climate model was developed for coupling with two-dimensional models of ocean circulation and stratospheric chemistry. Poleward and vertical transport of heat, moisture, and momentum by large-scale eddies have been parameterized using mixing length concepts based on conservation of potential temperature, water vapor, and potential vorticity. The hydrological cycle is explicitly simulated, including storage of soil moisture and snow. Land and ocean surfaces are distinguished in terms of their heat capacity and moisture-storage capacity. The ocean is presently represented as a simple mixed-layer slab. The model can account for both the diurnal and annual cycle in solar declination. Sea ice is presently crudely diagnosed in terms of ocean temperature. Cloud-radiation feedbacks

are treated through predictions of cloud cover and cloud liquid water and their impact on solar and terrestrial radiation.
Contacts: Karl E. Taylor, Peter J. Gleckler

Atmospheric Single-Column Model

We are developing a single-column model (SCM) option within the UCLA atmospheric general circulation model (AGCM). This option will allow the user to design and replicate field experiments or other finer-scale numerical simulations directly with the same components of a state-of-the-art climate model that is used for global-change research. This new capability is intended to support the development and validation of parameterizations of column-physics processes, in particular those of clouds and radiation. The model will be available to serve a diverse community of researchers who want to have the ready use of flexible combinations of computational components and experimental or other numerical data sets. Specifically, the SCM will provide for using measured data from experimental sites in place of the associated model components in order to more stringently constrain the remaining model components against their associated data. This work is proceeding in collaboration with the UCLA AGCM group.
Contact: James R. Albritton

Simplified Climate Model for Secondary School Education

This "toy" climate model is available for educational purposes. It is based on highly simplified radiative-transfer theory and has been tuned to give reasonably accurate estimates of globally averaged surface temperatures. The model currently runs on Macintosh computers in an interactive fashion that allows students to explore the influence on climate of such factors as CO_2 concentration, cloud cover, albedo, and water-vapor feedback. A speculative, semi-empirically based, sea-level model is also included.
Contact: Karl E. Taylor

Oceanic-Circulation Models

GFDL Modular Ocean Model

The National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model (MOM) is a finite-difference-based, global primitive-equation ocean-circulation model. The model is based on the original Bryan and Cox formulation. The code package features several compile-time options for choice of Poisson solver, vertical and lateral turbulent mixing parameterizations, and high-latitude filtering options. Versions have been created for execution on a range of hardware platforms, from UNIX workstations to Cray vector processors. A version is under development for execution on MIMD massively parallel systems, based on the (horizontal) domain decomposition/message-passing parallelization paradigm, as part of the U.S. Department of Energy's Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) model development program. The MOM is one of the baseline physics modules in LLNL's Earth Systems Modeling package.
Contact: William P. Dannevik

Global Eddy-Resolving Model

This model, developed by A. Semtner of the Naval Postgraduate School and R. Chervin of NCAR, is a direct descendant of the first oceanic GCM developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) over 20 years ago. In much the same way as atmospheric GCMs, this model calculates temperature, pressure, salinity, and current velocity on a three-dimensional global grid, given initial and boundary (surface-forcing and topography) conditions. Semtner and Chervin rewrote the GFDL code for efficient execution on parallel-processing vector supercomputers, allowing for high-resolution simulations that include the mesoscale oceanic eddies while retaining global coverage.
Contact: Curtis C. Covey

Isopycnic-Coordinate Model

This model was developed by J. M. Oberhuber of the Max Planck Institute ("Simulation of the Atlantic Circulation with a Coupled Sea Ice–Mixed Layer–Isopycnal General Circulation Model," submitted to *J. Phys. Oceanography*). The model uses density as a vertical coordinate, an advantage for oceanic GCMs because most of the oceans' mixing processes take place along surfaces of constant density. This model also incorporates submodels of the oceanic, upper mixed layer and sea ice (with rheology). The domain is easily adjustable from basin-wide to global. An implicit time-differencing scheme allows time steps as long as two days for 3° resolution. The model is now being run in cooperation with Tim Barnett of the Scripps Institution of Oceanography.
Contact: Curtis C. Covey

OSU Ocean General Circulation Model

This model, developed by J. Han at Oregon State University (OSU) and used in coupled atmosphere-ocean simulations by W. L. Gates et al. [Coupled Ocean-Atmosphere Models (Elsevier, 1985)], is a comprehensive six-level dynamical model of the global ocean circulation, with the option of an imbedded mixed layer. This model calculates the three-dimensional temperature, salinity,

current, and sea-ice distribution in response to prescribed surface forcing and bottom orography in much the same manner as the similar ocean models at GFDL. In its present configuration, this model has a horizontal resolution of 4° latitude and 5° longitude, and it requires about 60 min to simulate one year's time on a Cray-1 computer with a time step of 1 hr. Coupled to the OSU atmospheric GCM, this model is being used in extended integration to investigate natural variability and climate drift.
Contact: W. Lawrence Gates

Upper-Ocean Model

This model was developed by D. Pollard at Oregon State University [Performance of an Upper Ocean Model Coupled to an Atmospheric GCM: Preliminary Results. Climatic Research Institute, Oregon State University, Corvallis, OR, Report 31 (1982)]. This model is a two-layer model of the upper ocean and was used with a coupled atmospheric model in extended simulations for both normal and doubled CO_2 by W. L. Gates and G. L. Potter. The model calculates the horizontal current and temperature in a layer of variable depth representing the surface mixed layer and in an underlying layer (also of variable depth) representing the thermocline, with parameterized entrainment at their interface; sea ice is calculated under the constraint of prescribed salinity. In its present configuration, this model has a horizontal resolution of 4° latitude and 5° longitude, and it requires about 10 min to simulate one year's time on a Cray-1 computer with a time step of 1 hr.
Contact: W. Lawrence Gates, Gerald L. Potter

One-Dimensional Upwelling–Diffusion Model

This Sun Fortran program implements the one-dimensional ocean/climate model of Hoffert et al. [*J. Geophys. Res.*, **85**, 6667 (1989)]. Given an assumed atmospheric climate sensitivity and assumed magnitudes of turbulent mixing and large-scale overturning circulation in the ocean, the model will calculate ocean temperature as a function of depth and time for any scenario of greenhouse gas or other climate forcing.
Contact: Curtis C. Covey

Appendix E. Publications*

Journal Articles, Books, and Book Chapters

Atherton, C. S., and J. E. Penner, 1990: The effects of biogenic hydrocarbons on the transformation of nitrogen oxides in the troposphere. *J. Geophys. Res.*, **95**, 14 027–14 038.

Atherton, C. S., J. E. Penner, and J. J. Walton, 1991: The role of lightning in the tropospheric nitrogen budget: Model investigations. LLNL Report No. UCRL-JC-107223; *Geophys. Res. Lett.*, submitted.

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Chan, S. T., 1992: Numerical simulations of LNG vapor dispersion from a fenced storage area. *J. Haz. Mat.*, **30** 195–224.

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*List includes publications prepared in full or in part by AGS staff, consultants, subcontractors, and guests during 1990–91. Publications not listed in previous Program Reports are also listed. Send requests for selected reprints/reports to G-Division Librarian, Lawrence Livermore National Laboratory, P.O. Box 808, L-262, Livermore, CA 94551.

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Appendix F. Invited Seminar Speakers

Sam Iacobellis, Scripps Institution of Oceanography
"Diagnostic Modeling of the Indian Summer Monsoon"
February 12, 1990

James Coakley, Oregon State University
"Cloud Optical Properties and Climate"
February 22, 1990

David Burridge, European Centre for Medium Range Weather Forecasts, Reading, U.K.
"Systematic Errors of the ECMWF Model"
March 19, 1990

David Burridge, European Centre for Medium Range Weather Forecasts, Reading, U.K.
"Surface Fluxes and Some Recent Developments in Parameterization at ECMWF"
March 20, 1990

Ari Patrinos, U.S. Department of Energy
"Atmospheric Research Opportunities for the 1990s"
March 21, 1990

Albert Semtner, Naval Postgraduate School
"Aspects of Oceanic General Circulation and Climatic Applications from an Eddy-Resolving Global Oceanic General Circulation Model"
April 27, 1990

Michael Schatzmann, University of Hamburg, Federal Republic of Germany
"Heavy-Gas Dispersion Modeling for Risk Assessment Applications"
May 21, 1990

Garrett Campbell, Colorado State University
"The International Satellite Cloud Climatology Project Comparison with Clouds Simulated by GCMs"
May 31, 1990

Timothy Hogan, Naval Oceanographic and Atmospheric Research Laboratory
"NOGAPS: Description of and Sensitivity to Physical Parameterizations"
June 18, 1990

Robert Chatfield, NASA/Ames Research Center
"The Essential Role of Convection in the S and N Cycles: The Mechanics of the Tropospheric Ozone Hill and the Primary Cycling of Sulfur and Aerosol in the Remote Troposphere"
June 22, 1990

Tamas Prager, National Center for Atmospheric Research
"Sensitivity Analysis of Climate Models by the Adjoint Method"
July 9, 1990

Phil D. Jones and Tom M. L. Wigley, University of East Anglia, U.K.
"Are We Experiencing the Greenhouse Effect?"
July 12, 1990

Luis R-Mendez-Nuñez, University of California, Davis
"Application of the MacCormack Scheme to Atmospheric Nonhydrostatic Models"
July 12, 1990

Mark Green, University of California, Davis
"Objective Classifications of Surface Wind Patterns in Southern California and their Relationship to Pressure, Visibility, and Specific Humidity Fields"
July 18, 1990

Robert Cess, State University of New York, Stony Brook
"Interpretation of Seasonal Cloud-Climate Interactions Using Earth Radiation Budget Experiment (ERBE) Data"
July 27, 1990

Greg Rau, NASA/Ames Research Center
"$^{13}C/^{12}C$ in Marine Plankton as a Recorder of Ocean-Atmosphere CO_2 Concentration"
August 15, 1990

Alejandro Pares-Sierra, Kyozo Ueyoshi, John Roads, and Warren White, Scripps Institution of Oceanography
"Studies of Air-Sea-Land Interaction over Coastal California with High-Resolution Limited Area Models"
August 16, 1990

Sultan Hameed, State University of New York, Stony Brook
"Simple Explanations of Climatic Variability"
August 21, 1990

Sultan Hameed, State University of New York, Stony Brook
"Diagnostics of General Circulation Model Fields Using Harmonic Analysis"
August 23, 1990

Jean-Jacques Morcrette, European Centre for Medium Range Weather Forecasts, Reading, U.K.
"Impact of a New Radiation Scheme in the ECMWF Model"
August 30, 1990

Yizhak Feliks, Israel Institute for Biological Research
"Eddies and Downwelling in the Eastern Mediterranean Induced by Winter Storms"
September 25, 1990

V. Ramanathan, Scripps Institution of Oceanography
"Recent Satellite Observations of Cloud Radiative Forcing and the Atmospheric Greenhouse Effect"
October 4, 1990

Klaus Arpe, European Centre for Medium Range Weather Forecasts, Reading, U.K.
"The Hydrological Cycle in the ECMWF Short Range Forecasts"
October 16, 1990

Jinwon Kim, Oregon State University
"Influence of Mesoscale Topography on Atmospheric Flows"
October 30, 1990

Bryant McAvaney, Bureau of Meteorology Research Centre, Melbourne, Australia
"The BMRC Global Atmospheric Model: Results from a 10-Year Simulation"
November 27, 1990

Bryant McAvaney, Bureau of Meteorology Research Centre, Melbourne, Australia
"Sensitivity Experiments with the BMRC Model: Experiments with the 'Swamp Ocean' Version and the Fixed April, Variable Albedo Experiment"
November 28, 1990

Albert Semtner, Naval Postgraduate School
"Ocean Modeling"
January 9, 1991

Peter Gleckler, University of California, Davis
"Two-Dimensional Atmospheric Models"
January 31, 1991

L. D. Danny Harvey, University of Toronto
"Experiments with a Coupled Ocean-Atmosphere-Ice Model of Earth's Climate"
February 8, 1991

Larry Mahrt, Oregon State University
"A Simple Formulation for Boundary-Layer Cloud Cover"
February 22, 1991

John Brock, NASA/Goddard Space Flight Center
"Southwest Monsoon Upwelling, Phytoplankton Blooms, and Recent Foraminifera Ecology in the Northwest Arabian Sea"
March 4, 1991

Robert Cess, State University of New York, Stony Brook
"Cloud-Radiation Feedback"
March 28, 1991

Norman Hoffman, National Weather Service
"Modernization and Associated Restructuring of the National Weather Service"
April 4, 1991

Julia Slingo, National Center for Atmospheric Research
"Low-Frequency Oscillations"
April 11, 1991

Kenneth Patten, Jr., University of California, Berkeley
"Radiative Dynamics of Nitrogen Dioxide"
April 15, 1991

David Fleshman, Shaw Air Force Base
"The Persian Gulf War from a Pilot's Perspective"
April 16, 1991

Kenneth W. Johnson, Florida State University
"Analysis and Modeling of a Mountain Thunderstorm"
April 25, 1991

Peter Sousounis, Pennsylvania State University
"COLD Events: Straight Talk and Machine-Made Snow"
May 29, 1991

David Mitchell and Steve Chai, Desert Research Institute
"Parameterization of Cirrus and Marine Stratus Cloud Microphysics for GCMs"
June 6, 1991

Dingming Hu, University of Miami
"A Joint Mixed Layer/Isopycnic Coordinate Numerical Model of Wind-Driven Thermohaline Circulation with Sensitivity Study"
June 10, 1991

Robert Cess, State University of New York, Stony Brook
"Snow-Albedo-Temperature Feedback"
June 17, 1991

Ricky Rood, NASA/Goddard Space Flight Center
"Three-Dimensional Modeling of Atmospheric Transport in the Troposphere and Stratosphere"
June 27, 1991

Lori Perliski, NOAA/Aeronomy Laboratory
"Detailed Formulation of Radiative Transfer in the Stratosphere: Influence on Photochemistry and Interpretation of Zenith Sky Measurements"
July 1, 1991

David Bennetts, Hadley Centre, U.K.
"Climate Research at the Hadley Centre"
July 2, 1991

John Bartzis, National Center for Scientific Research, Institute of Nuclear Technology-Radiation Protection, Athens, Greece
"ADREA-I Mesoscale Modeling—Main Features and Recent Results"
July 25, 1991

Sultan Hameed, State University of New York, Stony Brook
"Statistical Analysis of Climate Simulations"
July 29, 1991

Lennart Thaning and Erik Nasland, National Defence Research Laboratory, Umea, Sweden
"Present and Future Work with the MATHEW/ADPIC Models at the National Defence Research Laboratory, Umea, Sweden"
July 31, 1991

Natalia Andronova, Main Geophysical Observatory, Leningrad
"Cause-and-Effect: Application to Photochemistry"
August 13, 1991

Julia Slingo, National Center for Atmospheric Research
"Analysis of 30–60 Day Oscillations"
August 23, 1991

Charles Quon, University of California, Los Angeles
"Multiple Equilibria in Thermosolutal Convection Due to Salt-Flux Boundary Condition"
August 26, 1991

Bryan Weare, University of California, Davis
"Why Use Old-Fashioned Marine Weather Reports in Cloud-Climate Research?"
August 26, 1991

Michael C. Morantine, Tulane University
"Upwelling Diffusion Climate Models: Analytical Solutions for Radiative and Upwelling Forcing"
August 27, 1991

Donald Eliason, University of Florida
"Coupling Numerical Circulation Models and Biogeochemical Models: Particle Flux in East Lagoon, Texas, and Sediment Transport in Lake Okeechobee, Florida"
August 28, 1991

K. J. Joseph Yip, Texas A&M University
"A Study of Equatorial 50-Day Oscillation in Simplified Community Climate Model"
August 29, 1991

Igor Mokhov, Academy of Sciences, Russia
"Analysis of Model Cloud Simulations"
September 23, 1991

Erich Mursch-Radlgruber, Universitat für Bodenkultur, Vienna, Austria
"Regional-Scale, Three-Dimensional Wind Field and Dispersion Modeling of Air Quality Problems in Austria"
September 27, 1991

Martin Hoffert, New York University
"Paleo-Calibration of Climate Change Models" and "Energy Research for the Greenhouse Century"
October 11, 1991

Kurt Fedra, International Institute for Applied Systems Analysis, Vienna, Austria
"Environmental Modeling and Climate Impact Assessment"
November 1, 1991

Hans-F. Graf, Max Planck Institute, Hamburg, Federal Republic of Germany
"Volcanoes and Climate: Facts and Models"
November 6, 1991

Prashant Sardeshmukh, University of Colorado
"Tropical Convective Forcing of the Atmosphere"
November 6, 1991

Sanford Sillman, University of Michigan
"Models for the Photochemistry of Ozone at the Urban, Regional, and Global Scale"
November 7, 1991

Prasad Varanasi, State University of New York, Stony Brook
"Infrared Spectra of Trace Species in Planetary Atmospheres at Relevant Temperatures"
November 8, 1991

George Kattawar, Texas A&M University
"The Atmosphere-Ocean Connection"
November 8, 1991

Niklas Schneider, University of Hawaii at Manoa
"The Sensitivity of the Yoshida Jet to Vertical Mixing Parameterization: Do Easterly Winds Imply Equatorial Upwelling?"
November 13, 1991

Howard LaGrone, State University of New York, Stony Brook
"The Effect of DMS and Isoprene on Reactive Nitrogen Chemistry"
November 21, 1991

Robert Cess, State University of New York, Stony Brook
"Use of ERBE Data in Climate Model Diagnosis"
December 19, 1991

Daniel Botkin, University of California, Santa Barbara
"Approaches to Improving Current Models of the Global Carbon Cycle"
December 19, 1991

Appendix G. Acronyms and Abbreviations

A	**ABL**	Atmospheric boundary layer
	ADPIC	Lagrangian particle advection-diffusion model
	AFGWC	U.S. Air Force Global Weather Central
	AFTAC	U.S. Air Force Technical Applications Center
	AGCM	Atmospheric general circulation model
	AGS	Atmospheric and Geophysical Sciences
	AMIP	Atmospheric Model Intercomparison Project
	ANATEX	Across North America Tracer Experiment
	ARAC	Atmospheric Release Advisory Capability
	ARAMCO	A contractor in Dhahran, Saudi Arabia
	ARG	Accident Response Group
	ARM	DOE's Atmospheric Radiation Measurement program
	ASCOT	DOE's Atmospheric Studies in Complex Terrain program
	ATMES	Atmospheric Transport Model Evaluation Study
B	**BAAQMD**	Bay Area Air Quality Management District
	BC	Black carbon
C	**CART**	Clouds and Radiation Testbed (a component of ARM)
	CCM	NCAR's Community Climate Model
	CCM1	NCAR's Community Climate Model (updated version 1)
	CEC	Commission of European Communities
	CFC	Chlorofluorocarbon
	CHAMMP	DOE's Computer Hardware, Advanced Mathematics, and Model Physics program
	CRDEC	U.S. Army, Chemical Research Development and Engineering Center
	CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
	CSU	Colorado State University
D	**DA**	Data assimilation
	DAS	Department of Applied Science at University of California, Davis/Livermore
	DDMP	Domain decomposition message-passing
	DOD	U.S. Department of Defense
	DOE	U.S. Department of Energy
	DOT	U.S. Department of Transportation
	DP	DOE/Office of Defense Programs
	DRS	Data Retrieval and Storage (a data-management system)
E	**ECMWF**	European Centre for Medium Range Weather Forecasts (U.K.)
	EEFC	Emergency Emissions Forecast Center
	EH	DOE/Office of Environmental Safety and Health
	EM	DOE/Assistant Secretary for Environmental Restoration and Waste Management
	ENUWAR	Environmental consequences of nuclear war (a SCOPE research program)
	EOC	DOE's Emergency Operations Center
	EOS	Earth Observing System (a NASA program)
	EPA	U.S. Environmental Protection Agency

	ER	DOE/Office of Energy Research
	ERBE	Earth Radiation Budget Experiment
	ERDA	U.S. Energy Research and Development Administration
	ESM	Earth Systems Model
F	**FANGIO**	Feedback Analysis for GCM Intercomparison and Observations
	FDAA	Four-dimensional data assimilation
	FEM	Finite-element method
	FEM3	Three-dimensional finite-element model
	FEM3A	Three-dimensional finite-element model (revised version A)
G	**G-CHEM**	PNL's global chemistry model
	GBAPM	WMO's Global Background Air Pollutants Monitoring program
	GCM	General circulation model
	GCRP	U.S. Global Change Research Program
	GFDL	NOAA's Geophysical Fluid Dynamics Laboratory
	GMS	General Measurement Strategy
	GRANTOUR	Three-dimensional aerosol Lagrangian parcel advection model
	GRI	Gas Research Institute
	GWP	Global warming potential
H	**HADPIC**	Hemispheric-scale Lagrangian particle advection-diffusion model
	HD	Hierarchical diagnosis
	HQ	DOE/Headquarters
	HSCT	High-speed civil transport aircraft
I	**INCOR**	UC's Institutional Collaborative Research program
	IPCC	Intergovernmental Panel on Climate Change
	IRF	Instantaneous radiative flux
	IVEP	Imperial Valley Environmental Project
L	**LAM**	Livermore Atmospheric Model
	LANL	Los Alamos National Laboratory
	LARC	Livermore Advanced Research Computer
	LDGO	Lamont-Doherty Geological Observatory
	LDRD	LLNL's Laboratory Directed Research and Development program
	LES	Large-eddy simulation
	LIRAQ	Livermore Regional Air Quality model
	LLNL	Lawrence Livermore National Laboratory
	LNG	Liquefied natural gas
M	**MAP3S**	Multistate Atmospheric Power Production Pollution Study
	MATHEW	Mass adjust the wind model
	MIMD	Multiple instruction, multiple data
	MLCCC	Multi-Laboratory Climate Change Committee
	MOM	GFDL's Modular Ocean Model
	MPC	Massively parallel computer
N	**NAPAP**	National Acid Precipitation Assessment Program
	NARE	North Atlantic Regional Experiment
	NASA	U.S. National Aeronautics and Space Administration
	NCAR	National Center for Atmospheric Research
	NE	DOE/Nuclear Energy
	NERSC	LLNL's National Energy Research Supercomputer Center

	NES	National Energy Strategy
	NIGEC	National Institute for Global Environmental Change
	NMC	NOAA's National Meteorological Center
	NMHC	Nonmethane hydrocarbon
	NOAA	U.S. National Oceanic and Atmospheric Administration
	NR	DOE/Assistant Secretary for Nuclear Energy, Office of Naval Reactors
	NSY	Naval Shipyards
	NTS	Nevada Test Site
O	**OCTET**	Three-dimensional, cloud and mesoscale dynamics model
	ODE	Ordinary differential equation
	ODP	Ozone depletion potential
	OES	California's Office of Emergency Services
	OGCM	Oceanic general circulation model
	OHER	DOE/Office of Health and Environmental Research
	ORNL	Oak Ridge National Laboratory
	OSU	Oregon State University
P	**PBL**	Planetary boundary layer
	PCMDI	Program for Climate Model Diagnosis and Intercomparison
	PDE	Partial differential equation
	PE	DOE/Assistant Secretary for Domestic and International Energy Policy, Office of Environmental Analysis
	PNL	Battelle Pacific Northwest Laboratory, Richland, WA
	PSAC	U.S. President's Science Advisory Council
R	**RADPATH**	Biogeochemical pathways of artificial radionuclides (a SCOPE research program)
S	**SABLE**	Simulator of the Atmospheric Boundary Layer Environment (a model)
	SCM	Single-column model
	SCOPE	Scientific Committee on Problems of the Environment
	SLAB	Dense-gas dispersion model
	SNLL	Sandia National Laboratories, Livermore
	SOAC	Satellite Ozone Analysis Center
	SST	Sea-surface temperature
	SST	Supersonic transport
T	**T(D)ARP**	Two Dimensional Atmospheric Research Program (a computer model)
	TERRA	Terrestrial ecosystem productivity and biogeochemcial cycling model
	TIVFS	Transient Incompressible Viscous Flow Simulator (a code)
	TMD	Theater Missile Defense
	TMI	Three Mile Island (nuclear reactor in Pennsylvania)
U	**UARS**	Upper Atmosphere Research Satellite
	UC	University of California
	UCD	University of California, Davis
	UCLA	University of California, Los Angeles
	U.K./MOD	United Kingdom's Ministry of Defence
	USA	U.S. Army
	USAF	U.S. Air Force
	USN	U.S. Navy
W	**WHO**	World Health Organization
	WMO	World Meteorological Organization